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Charnockite "In the Breaking" and "Making" in Kerala, South India: tectonic and microstructural evidences

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(With 32 Figures)

Abstract

Preliminary analysis of tectonics and microstructures of the interbedded charnockite-khondalite-leptynite sequence at three quarries of south Kerala shows four main events, namely, (1) An alternated sequence of rocks, which includes intrafolially folded (f_1) banded acid to basic rocks (original rocks of the banded charnockite) and quartz-feldspathic rocks (original rocks of the garnet gneiss) suffered the flexural slip folding (f_2) of the close to isoclinal type, followed by the annealing recrystallization resulting in the formation of a small-grained polygonal structure, these episodes resulting in the formation of the folded alternated sequence of the banded charnockite-garnet gneiss, (2) development of open to close passive folds with the axial plane foliation/schistosity in the banded charnockite (f_{3a}), and in the garnet-biotite gneiss (khondalite) and garnet gneiss (leptynite) (f_{3b}), associated with the transformation of the charnockite to the garnet gneiss through the garnet-biotite gneiss ("breaking") and the mobilization and intrusion of the garnet gneiss paralleling the axial surface of the f_3 folds and, (3) development of the garnetiferous quartz-feldspathic pegmatite and incipient pegmatitic charnockite patches ("making") associated with quasi-ductile deformation of the garnet-biotite gneiss and (4) intrusion of the biotite pegmatite with faint schistosity, possibly associated with widespread but faint alterations.

The breaking event postdates the isoclinal folding and the formation of the banded charnockites, but predates the making of the pegmatitic charnockite. The breaking and making of charnockites may be widespread in south Kerala and denote repeated tectonic-metamorphic episodes resulting in a prolonged crustal stabilization history in this part of the Indian shield which appears to be common with that of the plutono-metamorphic sequence surrounding Mysore.

INTRODUCTION

The Kerala region forms the south-western part of the Indian shield and comprises a significant segment of the Precambrian granulite facies terraine of south India (Figs. 1A, B). Consisting dominantly of interbedded orthopyroxene and garnet bearing granulites (charnockites), garnet-biotite ± sillimanite ± cordierites bearing gneisses (khondalites) and garnetiferous quartz-feldspathic gneisses (leptynites), the region offers a challenging area for investigations related to metamorphic petrology, tectonics and Precambrian crustal evolution (e.g. Sinha-Roy, 1983, Srikantappa et al., 1985, Santosh, 1986).

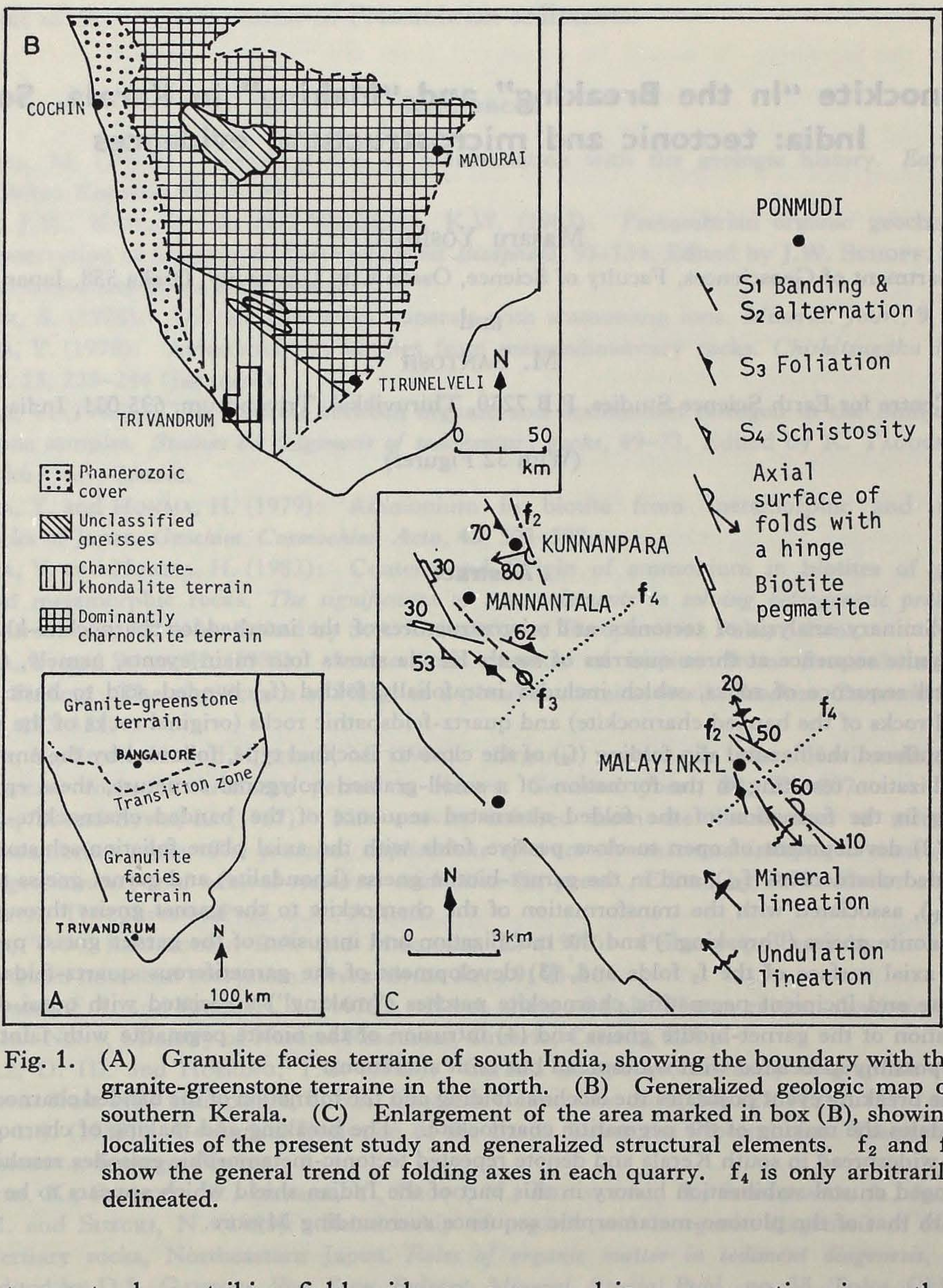

Fig. 1. (A) Granulite facies terraine of south India, showing the boundary with the granite-greenstone terraine in the north. (B) Generalized geologic map of southern Kerala. (C) Enlargement of the area marked in box (B), showing localities of the present study and generalized structural elements. f_2 and f_3 show the general trend of folding axes in each quarry. f_4 is only arbitrarily delineated.

Recent reports show striking field evidences preserved in quarry sections in south Kerala, of progressive transformation of khondalites and leptynites to charnockite in some localities (KUMAR et al., 1985, SRIKANTAPPA et al., 1985) and retrogressive transformation of charnockites to khondalites and leptynites in some others (SANTOSH and YOSHIDA, 1986), even though no serious attempts have been made to study the interrelationships of both the processes in relation to regional tectonics. We present here the tectonic and microstructural evidences of the charnockite "in the breaking" and the charnockite "in the making" from three quarry sections around Trivandrum in south Kerala, namely, Malayinkil, Kunnanpara and Mannantala (Figs. 1C, 2, and 3), where the processes related to

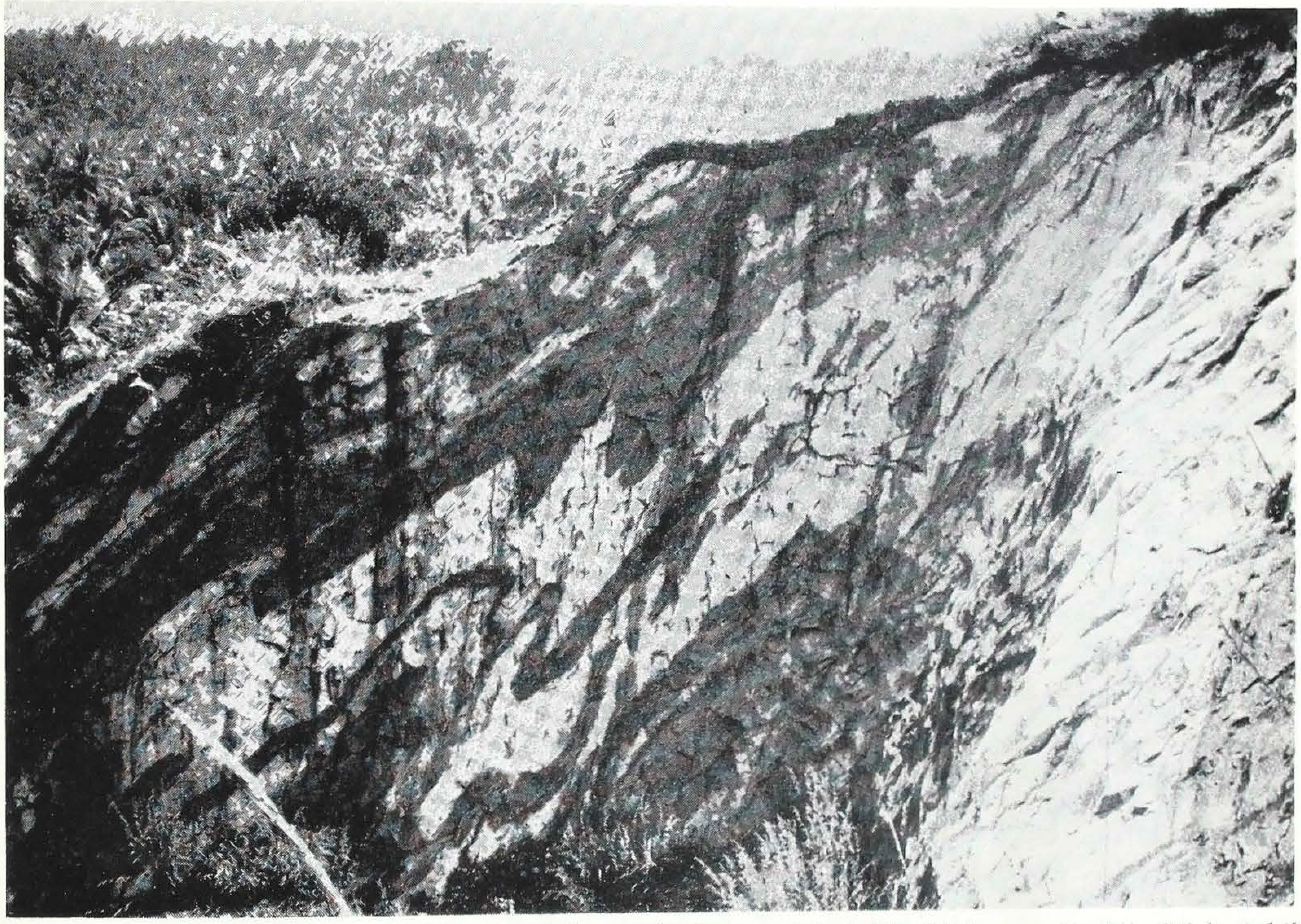

Fig. 2. Charnockite - garnet gneiss alternation with close to tight folds (f_2) (east wall of the Malayinkil quarry).

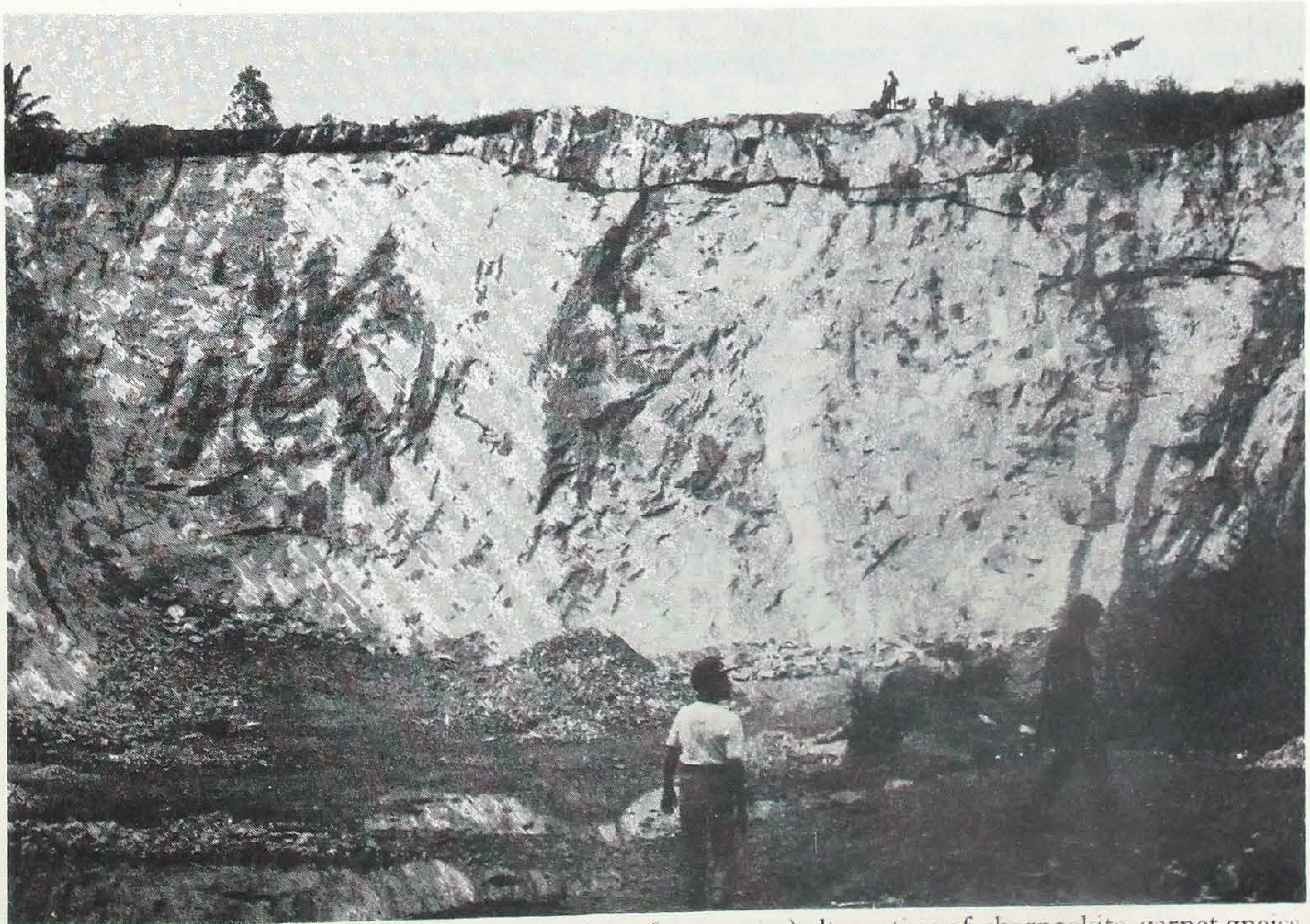

Fig. 3. Paleozomic folded (f_2, modified by later f_3 tectonics) alternation of charnockite-garnet gneiss (north wall of the Kunnanpara quarry).
In this outcrop, the mobilization of the garnet gneiss is dominant (cf Fig. 12).

both deep crustal metamorphism and recurrent tectonic events are well preserved.

GEOLOGICAL AND STRUCTURAL SETTINGS

Geology

In the study area are developed charnockites, garnet-biotite gneiss, and garnet gneiss. The former rock is included in the Charnockite Group and the latter two, in the Khondalite Group widely distributed in south Kerala (SOMAN 1980). These rocks often show gradational occurrences, exhibitting the breaking of the charnockite into the gneisses, as well as the making of the charnockite from the gneisses (Figs. 4~11).

The charnockites consist of the banded charnockite and the pegmatitic charnockite, both of which are dark rock with a greasy appearance containing more or less orthopyroxene. The banded charnockite is found widely in both the Malayinkil and Kunnanpara quarries. It is compositionally banded with some centimeters to several decimeteres thickness composed of small (0.3–1.0 mm in diameter)- to medium (1.0–3.0 mm)-grained mafic or intermediate facies and coarse (3.0–10.0 mm)-grained quartz-feldspathic facies. The quartz-feldspathic band is a prominent structure of the banded charnockite. The banding structure of the banded charnockite is generally roughly parallel to the alternation structure; but small disparallelism is often the case and clear discordancy is also not rare. In such cases, the banding of the banded charnockite is cut by the garnet gneiss which alternates with the banded charnockite. The banding of the banded charnockite sometimes exhibits tight to isoclinal folds of the similar type. Some of the quartz-feldspathic bands of the banded charnockite change into veins and crosscut the banded structure of the charnockite. These structures are also circumscribed within the banded charnockite layer. The banded charnockite generally alternates with the garnet gneiss although in some cases, the former grades into, or is cut by the latter. A unit of a layer of the banded charnockite ranges from some decimeters to several meters in width as does that of the garnet gneiss, although the latter is generally thicker than the former. Layers of the banded charnockite, along with the alternated garnet gneiss, generally suffered mesoscopic close to isoclinal folds of possibly the flexural slip type and later suffered minor to mesoscopic foldings of the passive type.

The pegmatitic charnockite occurs mainly at the Mannantala quarry. It is a coarse-grained, homogeneous, massive or weakly foliated rock bearing garnet, biotite and orthopyroxene. It forms discontinuous neozomic patches of irregular shape of few decimeters in thickness and some decimeters to tens of meters in length embedded within the migmatitic, thinly banded garnet-biotite gneiss. The distribution of these patches appears to follow some pattern of fractures.

The garnet-biotite gneisses consist of thinly banded garnet-biotite gneiss and heterogeneous garnet-biotite gneiss. The thinly banded garnet-biotite gneiss widely occurs at the Mannantala quarry. It is small-grained and banded by relatively quartz-feldspar-rich and garnet-biotite-rich bands of some millimeters in thickness. Bands, pools, or veins

Fig. 4. Charnockite/garnet gneiss alternation (northeastern wall of the Malayinkil quarry). Banding of the banded charnockite (dark layer), heterogeneity and foliation of the garnet gneiss (light layer) and schlieric dark block. Part of the banded charnockite (lower band, dark) fades into the garnet gneiss through the garnet-biotite gneises (dark, intermediate position).

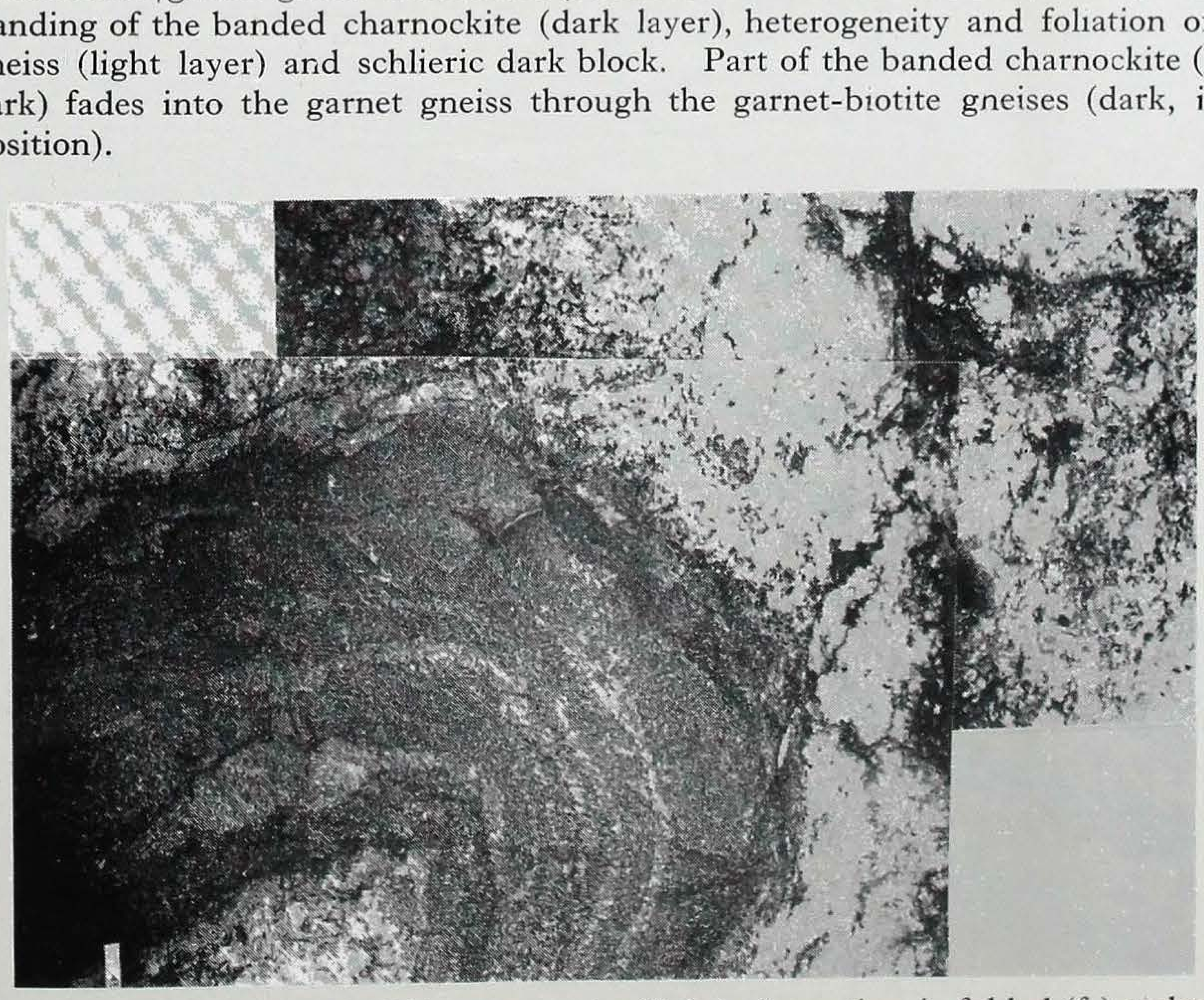

Fig. 5. A banded charnockite (dark)/garnet gneiss (light) alternation is folded (f_2) tighty (east wall of the Malayinkil quarry, one of the crestal portion of folds shown in Fig. 2). The foliation of the garnet gneiss runs from the upper right to the lower left. The banding of the banded charnockite and the foliation of the garnet gneiss are discordant. The charnockite changes to the garnet-biotite gneiss at the right-upward protruded portion of the folded charnockite layer into the garnet gneiss (cf. Figs. 11 and 16).

Fig. 6.

Fig. 7.

Fig. 6. Banded charnockite/garnet gneiss alternation suffered open to cloes f_2 folds (west wall of the Malayinkil quarry).
Some of the charnockite layers (dark) are disappearing into the garnet gneiss (light). Layers of the banded charnockite appear to have suffered isoclinal folding (upper left) prior to the f_2 fold.

Fig. 7. The folded banded charnockite (dark) is breaking into the heterogeneou, foliated garnet gneiss (light) through the garnet-biotite gneiss (intermediately dark layer) (southern hill just above the Malayinkil quarry, cf. Fig. 17).
The outcrop is nearly horizontal and so is the hinge of the fold; the variations of thickness of layers seen in this picture is resulted from this orientational relationship.

Fig. 8.

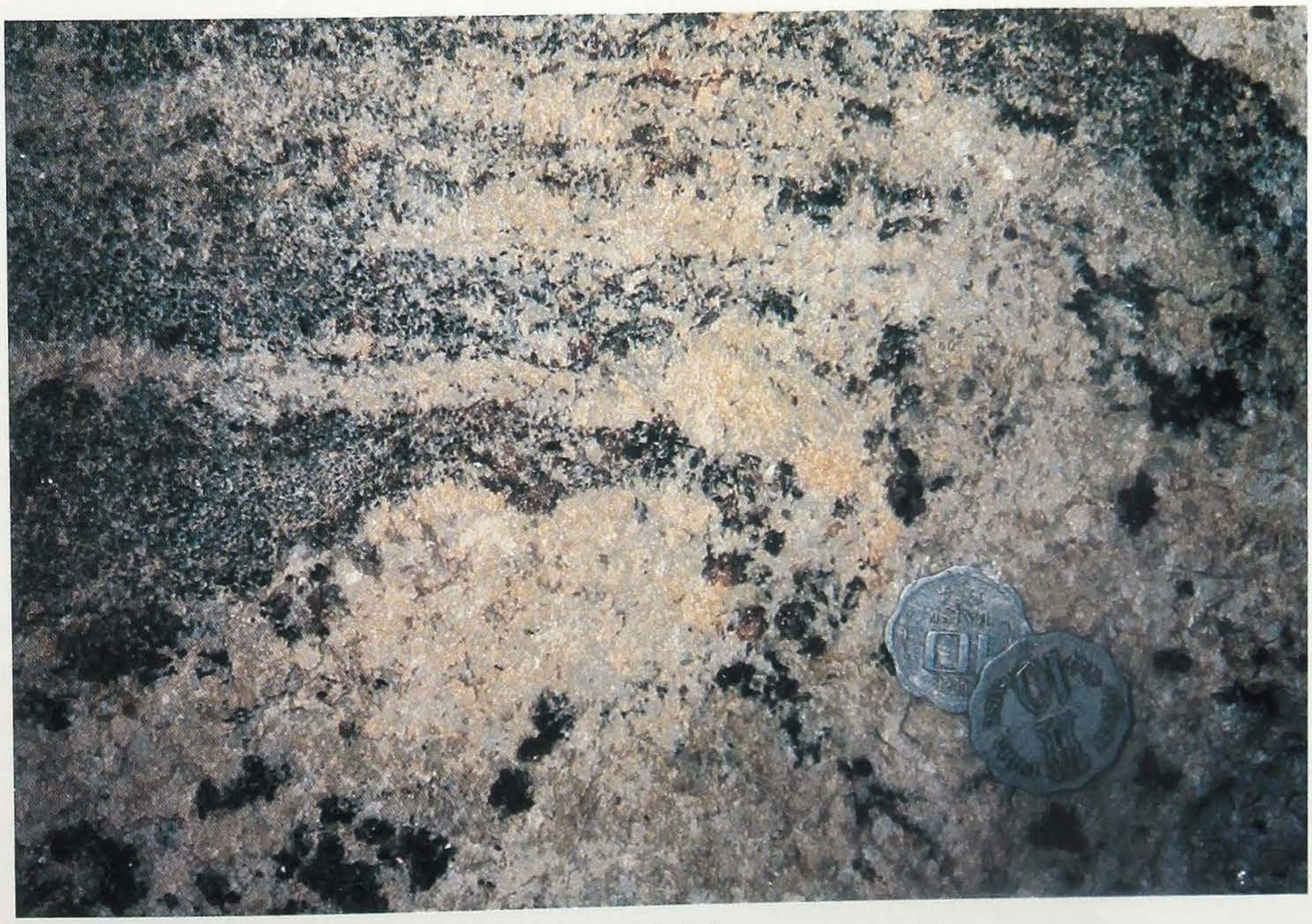

Fig. 9.

Fig. 8. The banded charnockite (lower right darker portion) changes to the garnet-biotite gneiss with bands of the garnet gneiss (upper left portion, relatively light colored) (lower part of Fig. 7).

Fig. 9. The garnet-biotite gneiss (upper left) is disappearing into the garnet gneiss (lower right). Coarse clusters of garnet and biotite are relatively dominant around the boundary (upper part of Fig. 7).

Fig. 10. Isoclinally folded alternation of the banded charnockite/garnet gneiss (east wall of the Malayinkil quarry, cf. Fig. 16).
Later disturbarce resulting in the small-scale passive folds (f_{3a}) and associated axial plane foliation (s_{3a}) over the isoclinal fold (f_2) is dominant. An unfolded part of the banded charnockite (centre) is altered into the garnet-biotite gneiss.

Fig. 11. Retrogression of the charnockite (very dark, left-most part) into the garnet gneiss (light, right half) through the garnet-biotite gneiss (dark, around the top of the pencil) (lower left part of Fig. 10; the figure orientation is rotated).

of garnet granitic pegmatite develop throughout. The quartz-feldspar rich band of the thinly banded garnet-biotite gneiss continues to the garnet granitic pegmatite. These features indicate the progressive migmatitic nature of the rock resulting in the formation of the garnet gneissose pegmatite. Mesoscopic to small scale open to close folds of the passive type develop dominantly. The garnet granitic pegmatite sometimes changes to the garnet gneissose pegmatite and intrudes along the axial surface of the folds.

The heterogeneous garnet-biotite gneiss occurs at the Malayinkil and Kunnanpara quarries. It is a medium-grained and massive, banded, or foliated rock, with varying amounts of garnet, biotite, quartz and feldspars. It occurs either at the boundary between the banded charnockite and the garnet gneiss or as schlieric layers or lenses within the garnet gneiss.

The garnet gneiss occurs at the Malayinkil and Kunnanpara quarries, alternating or is mixed with layers or blocks of the banded charnockite. It is a leucocratic quartz-feldspathic rock with a very small amount of garnet and biotite. Garnet and biotite are often aggregated to form lensoidal bodies or pools of some centimeters in length which represent the foliated character of the gneiss. Many parts of the rock are massive and very coarse-grained, and appear as pegmatitic. Intrusive or mobilized occurrence of this rock along the axial surface of some folds is not rare throughout the rock; the intrusive or mobilized portion is termed the garnet gneissose pegmatite.

Structures

Rocks of the present region contain several kinds of planar structures which have often suffered foldings of several kinds. The planar structures include the following four kinds.

i) Banding (s_1) represented by the alternation of either the quartz-feldspathic charnockite and basic-intermediate charnockite (Figs. 4, 5, and 7) constituting the banded charnockite (some decimeters thick), or garnet-biotite-rich and quartz-feldspar-rich facies developed in the thinly banded garnet-biotite gneiss (some millimeters thick); ii) alternation (s_2) represented by the alternation of layers of the banded charnockite and the garnet gneiss (Figs. 2, 3 and 4) several decimeters to several meters thick. It is worthy of note that the banding, as well as the intrafolial folding structures of the banded charnockite is often cut by the garnet gneiss alternating with the banded charnockite; iii) foliation (s_{3a} and s_{3b}) characterized by the leaf-like clots (generally some millimeters in size) of garnet and/or biotite aggregates, developed in the garnet gneiss (Figs. 5, 7, 10 and 11); and iv) schistosity characterized by the lattice preferred orientation of planar minerals more or less developed in almost all rocks of the present study. This plane is formed in various ways. The youngest one (s_4) is the NW-SE schistosity formed possibly by the rotation of pre-existent biotite or the growth of new biotite during some later tectonic event than the f_3 folding events. In the charnockite or in the gneisses, some biotites are arranged more or less parallel to the banding, and some others are arranged parallel to the foliation. These schistosities are formed either during the formation of the

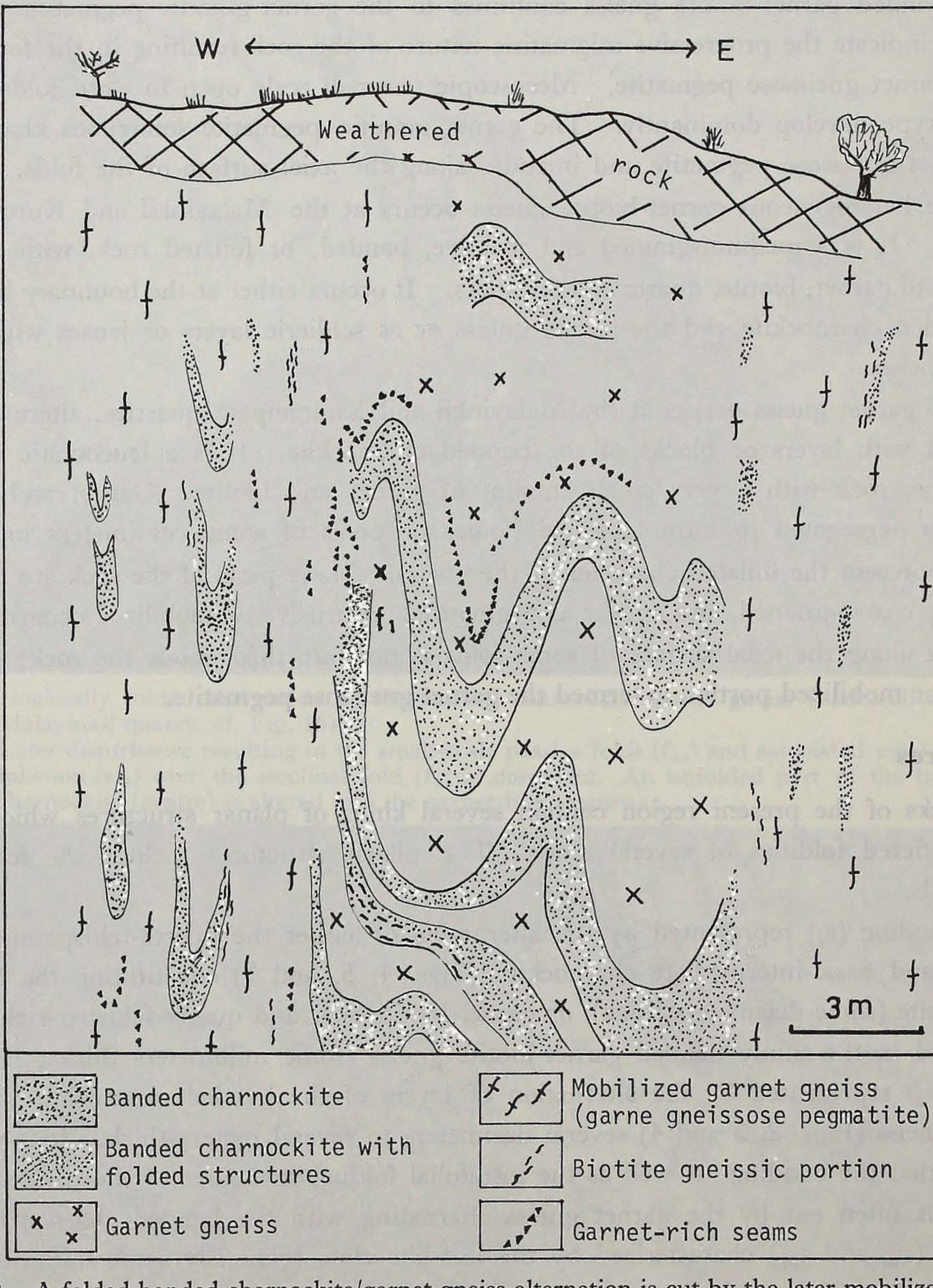

Fig. 12. A folded banded charnockite/garnet gneiss alternation is cut by the later mobilized garnet gneiss (north cliff of the Kunnanpara quarry, cf. Fig. 3).
The main folding structure of this outcrop belongs to the f_2, but it is modified by the f_{3a} event resulting in the refolding and development of the axial plane foliation, and later, in the mobilization of part of the garnet gneiss. Small intrafolial folds (f_1) develop at the margin of the charnockite band just left of the letter f_1. The axial surfaces of the main folds strike ca N15°W and dip 75° to the west, and the foliation dominated in the garnet gneissose pegmatite runs N40°W82°E. An axial surface of an isoclinally folded block at the left portion strikes ca N5°W and dips 75°E; this trend may indicate a modification of the f_2 folds by the f_{3a} tectonics.

s_1, s_2 or s_3 structures respectively, although they might have been affected by the later recrystallization in a mimetic fashion and thus, not showing complete parallel growth such as the lepidoblastic fabric.

Foldings observed in the present area include the following four kinds, although detailed analysis on the characterization of these folds are not made. To them are arbitrarily attached f_1 to f_4 numbers according to their estimated order of formation.

Small tight to isoclinal intrafolial folds (f_1) develop sporadically in some charnockite layers (cf. Fig. 12). We arbitrarily consider these folds to be the earlier folds than the f_2 folds following the interpretation by SINHA-ROY (1983). But another possibility is not eliminated that they are the drag folds associated with the f_2 folds.

Close to isoclinal folds of possibly the flexural slip type (f_2) (cf. Figs. 2, 3, 5, 12 and

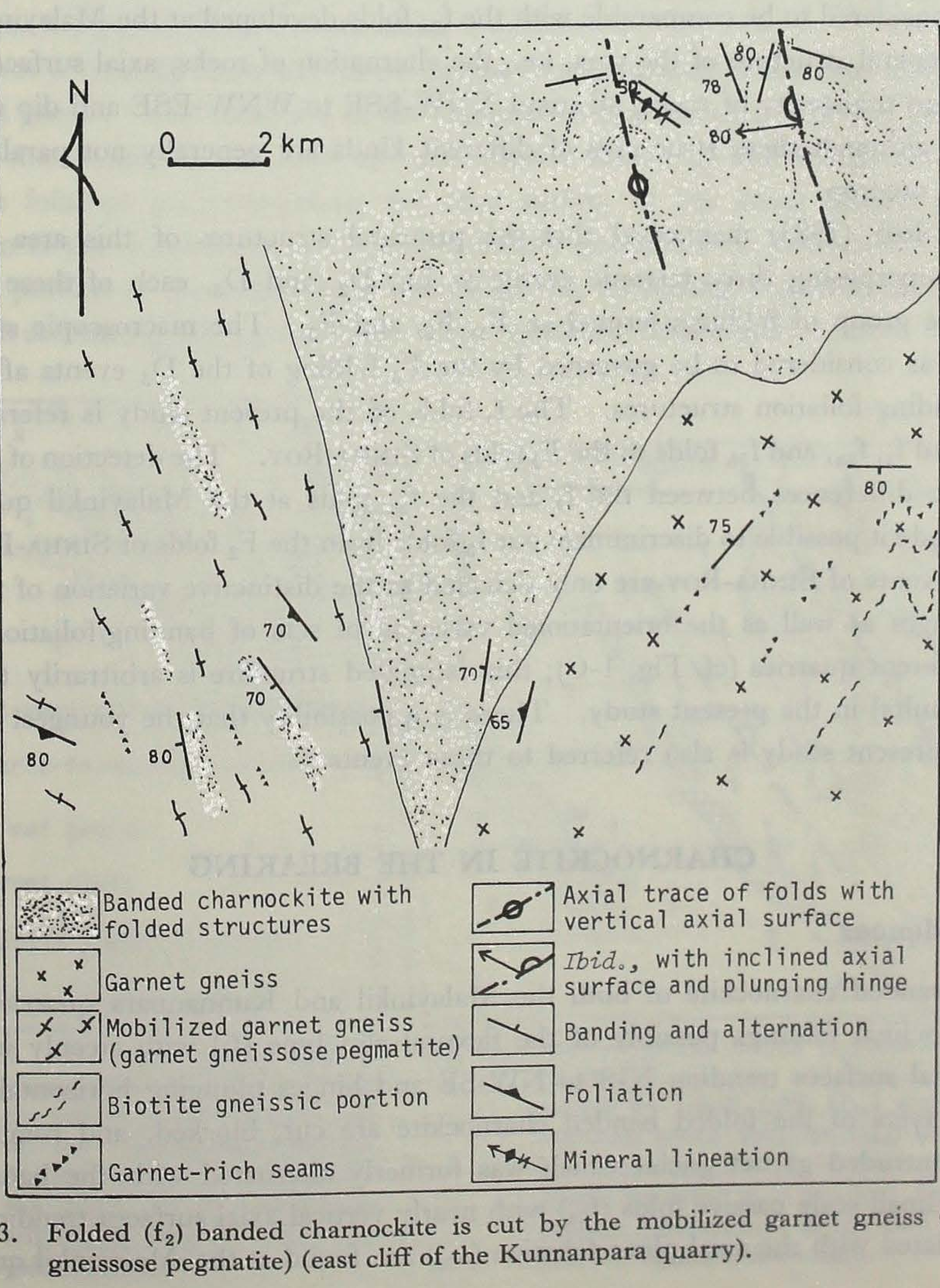

Fig. 13. Folded (f_2) banded charnockite is cut by the mobilized garnet gneiss (garnet gneissose pegmatite) (east cliff of the Kunnanpara quarry).

13) with some meters of wavelength are widely developed over the alternation of the charnockite and the garnet gneiss at the Malayinkil and Kunnanpara quarries. The development of the banded structures paralleling the folds, roundness of the folding knees as well as the near-constancy of thickness of layers in the folds indicate the folds to be the flexural slip type. Small folds of possibly the passive type (f_{3a}) are developed in the banded charnockite attached to or embedded in the garnet gneiss at the Malayinkil quarry (cf. Figs. 10, 15 and 16). Foliation (s_{3a}) paralleling the axial surface of these folds is found in the garnet gneiss. Some of the f_2 folds are rotated or refolded by these folds. Open to close folds of possibly the passive type (f_{3b}) with some centimeters to several meters of wavelength develop in the thinly banded garnet-biotite gneiss as well as in some garnet gneiss at the Mannantala quarry. They are the similar folds with somewhat acute folding knees and with foliation and schistosity (s_{3b}) paralleling the axial surface. These folds are considered to be comparable with the f_{3a} folds developed at the Malayinkil quarry.

The general structure of the area, i.e., the alternation of rocks, axial surfaces of folds, foliation, and schistosity of rocks, all trend NNW-SSE to WNW-ESE and dip moderately to steeply, although these structures of different kinds are generally not parallel to each other in an outcrop.

SINHA-ROY (1983) mentioned that the principal structures of this area is derived from the superposing three tectonic events as D_1, D_2, and D_3, each of these events including one group of foldings termed as F_1, F_2, and F_3. The macroscopic structure of this area was considered to be governed by the F_3 folding of the D_3 events affected over the D_2 banding-foliation structures. The f_1 folds of the present study is referable to the F_1 folds, and f_2, f_{3a}, and f_{3b} folds to the F_2 folds of SINHA-ROY. The detection of geometric-chronologic differences between the f_2 and the f_{3a} folds at the Malayinkil quarry (e.g., Fig. 15) made it possible to discriminate our f_3 folds from the F_2 folds of SINHA-ROY. The D_3 or D_4 events of SINHA-ROY are only detected as the distinctive variation of the plunge of fold hinges as well as the orientational variation of sets of banding/foliation/lineation among different quarries (cf. Fig. 1-C); this estimated structure is arbitrarily taken as f_4 (folds or faults) in the present study. There is a possibility that the youngest schistosity s_4) of the present study is also referred to these events.

CHARNOCKITE IN THE BREAKING

Field Evidences

The banded charnockite of both the Malayinkil and Kunnanpara quarries suffered close to isoclinal foldings possibly of the flexural slip type (f_2) with steeply inclined to vertical axial surfaces trending N-S to NW-SE and hinges plunging horizontally to vertically. Layers of the folded banded charnockite are cut, blocked, and rotated by the mobilized/intruded garnet gneiss which was formerly alternated with the banded charnockite. Small scale passive folds (f_{3a}) with nearly vertical axial surfaces trending NNW-SSE associated with the axial plane foliation (s_{3a}) are found at the Malayinkil quarry, and the similar vertical foliation trending toward WNW-ESE is found at the Kunnanpara quarry. The breaking down of the charnockite into the garnet-biotite gneiss and garnet gneiss is well documented everywhere associated predominantly with such younger structures as f_{3a} folds or the associated foliation. Some of which will be explained in some detail below.

Figure 14 is a part of a discontinuous relic layer of the garnet-biotite charnockite embedded within the garnet gneiss. The garnet-biotite gneiss is distributed as a continuation of, paralleling and/or fringing the layer of the charnockite. The garnet-quartz-feldspar pegmatite develops over the quartz-feldspathic bands of the charnockite and continues to the country garnet gneiss, cutting the schlieric garnet-biotite charnockite and garnet-biotite gneiss. The pegmatite resembles to the garnet gneiss in lithology and grades into it. Thus, the formation of the garnet gneiss through garnet-biotite gneiss from the garnet-biotite charnockite is estimated.

Figures 15 and 16 show the folded (f_2 and f_3) and banded charnockite alternating with the garnet gneiss. The structure of the charnockite and the garnet-biotite gneiss derived from the charnockite is disturbed by small passive folds (f_{3a}) and the garnet gneiss possesses the foliation (s_{3a}) paralleling the axial surface of the small passive folds. The conversion of the charnockite to the garnet-biotite gneiss is seen dominantly at the more disturbed portion of the charnockite layer (Fig. 16), indicating a correlation between the conversion and the f_{3a} folding tectonics. The "unfolded" charnockite - garnet-biotite gneiss

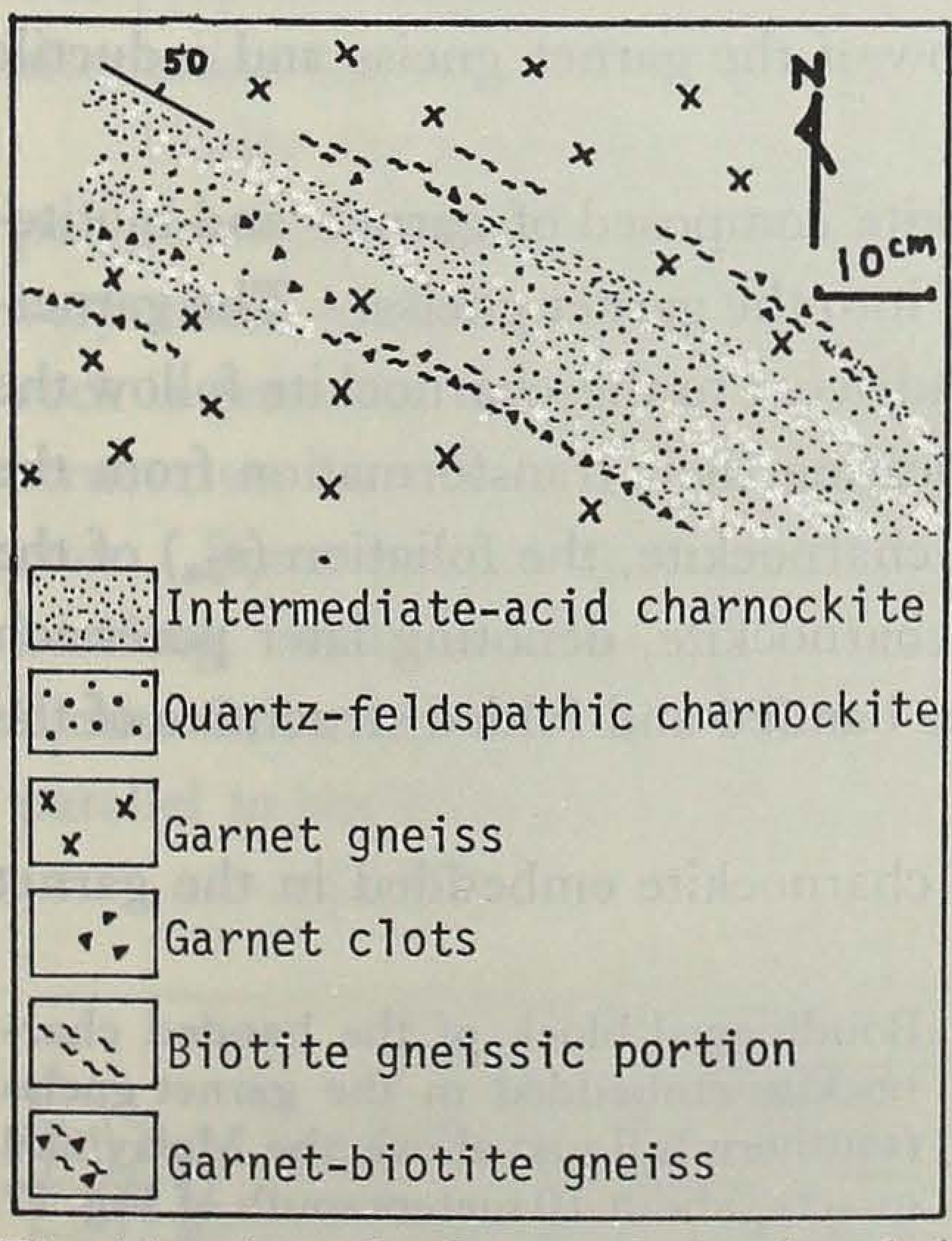

Fig. 14. A relic layer of the banded charnockite embedded within the garnet gneiss (western cliff of the Malayinkil quarry). Notice that the quartz-feldspathic bands of the charnockite selectively change into the garnet gneiss.

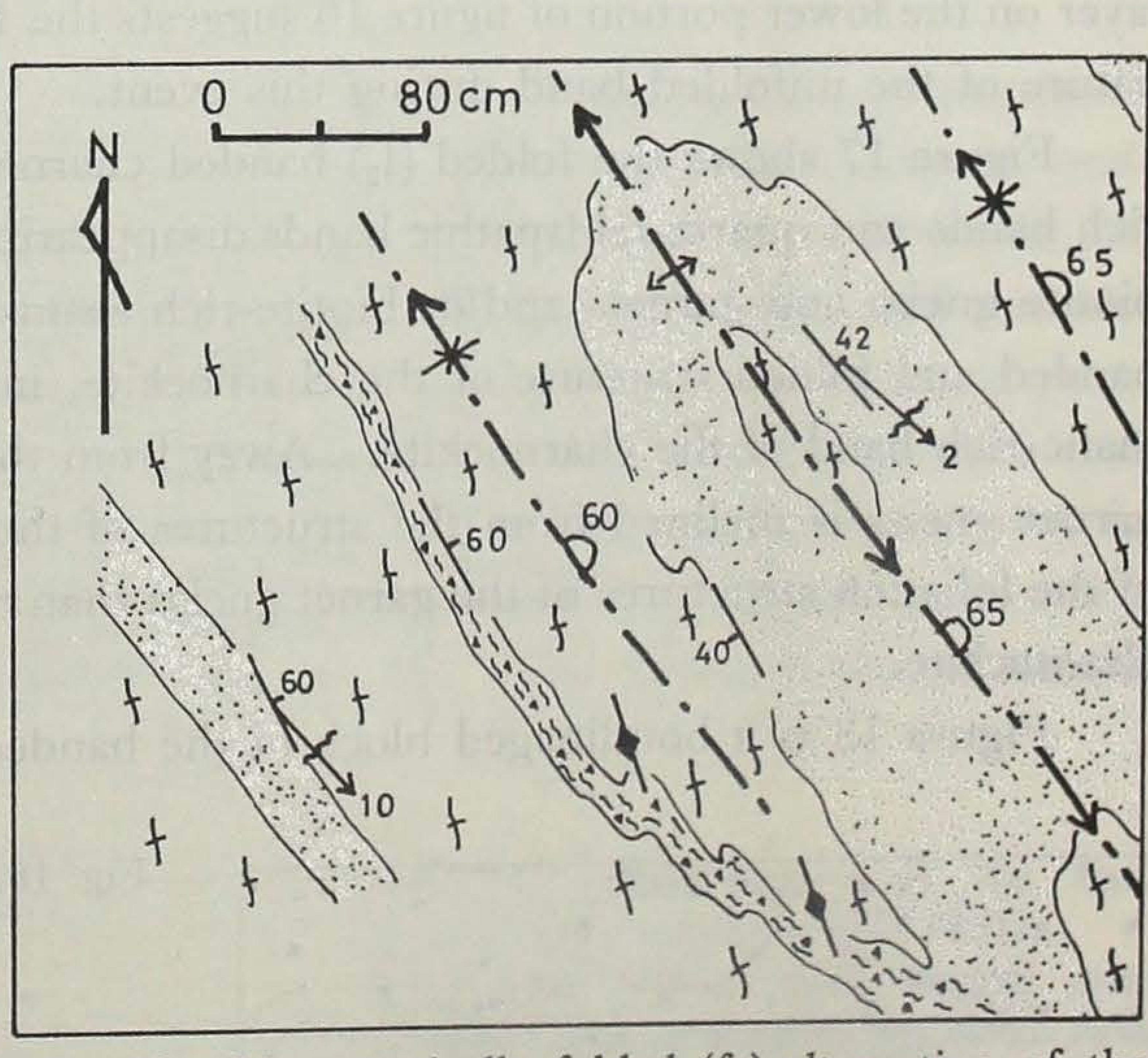

Fig. 15. Mesoscopically folded (f_2) alternation of the banded charnockite and garnet gneiss is disturbed by small folds (f_{3a}) associated with the axial plane foliation (s_{3a}) (southern hill just above the Malayinkil quarry).
Marks are same as in previous figures. Note that the axial surface of the fold (f_2) and the foliation (s_{3a}) are discordant.

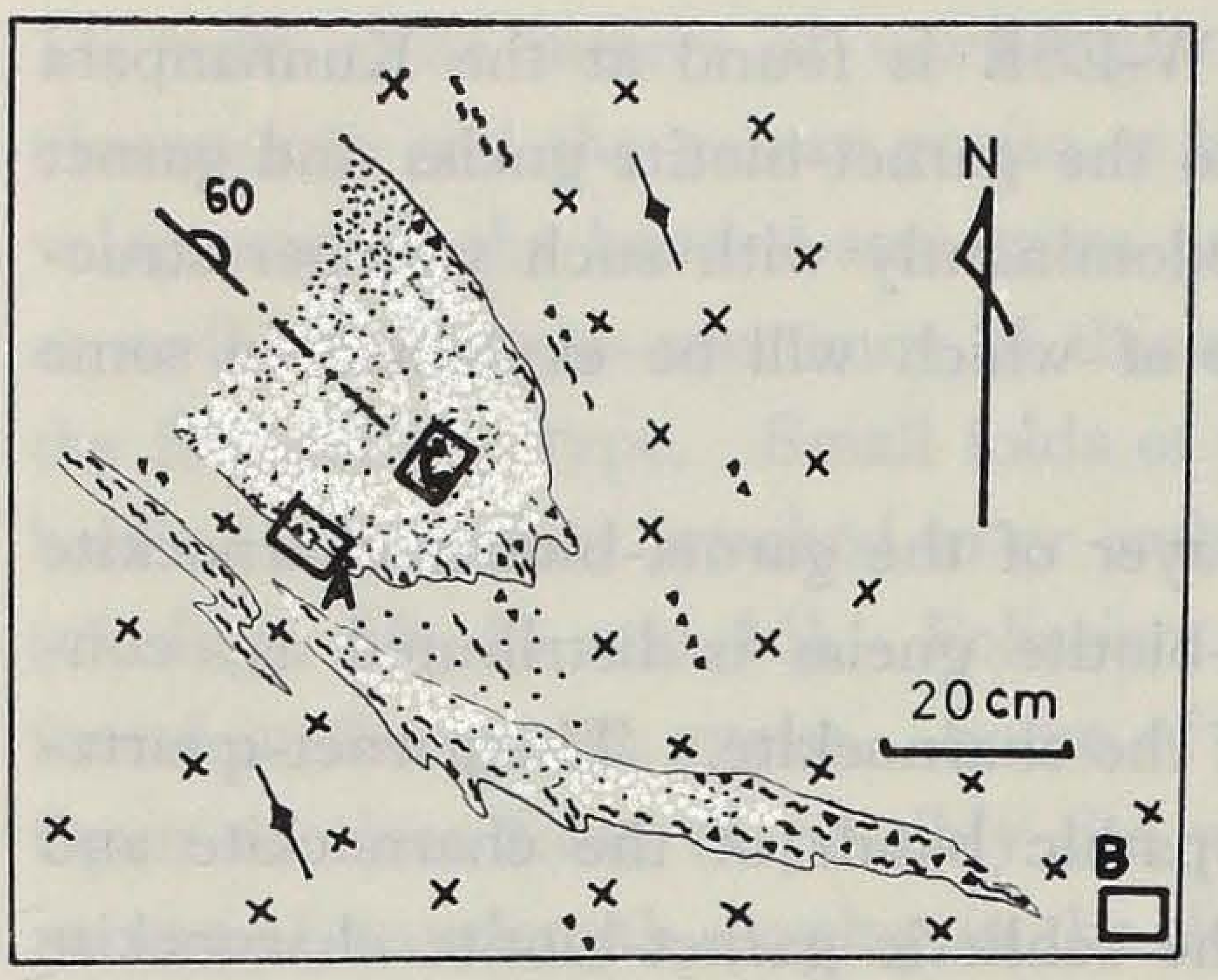

Fig. 16. Small passive folds (f_{3a}) and associated foliations (s_{3a}) superimposed over the former isoclinal folds (f_2) (southern part of the east cliff of the Malayinkil quarry, cf. Figs. 10 and 11). Squares A and C indicate the similar structural positions where specimens 86010301A and 86010301C were collected respectively. Square B is the location of the specimen 86010301B. Other marks are same as in previous figures.

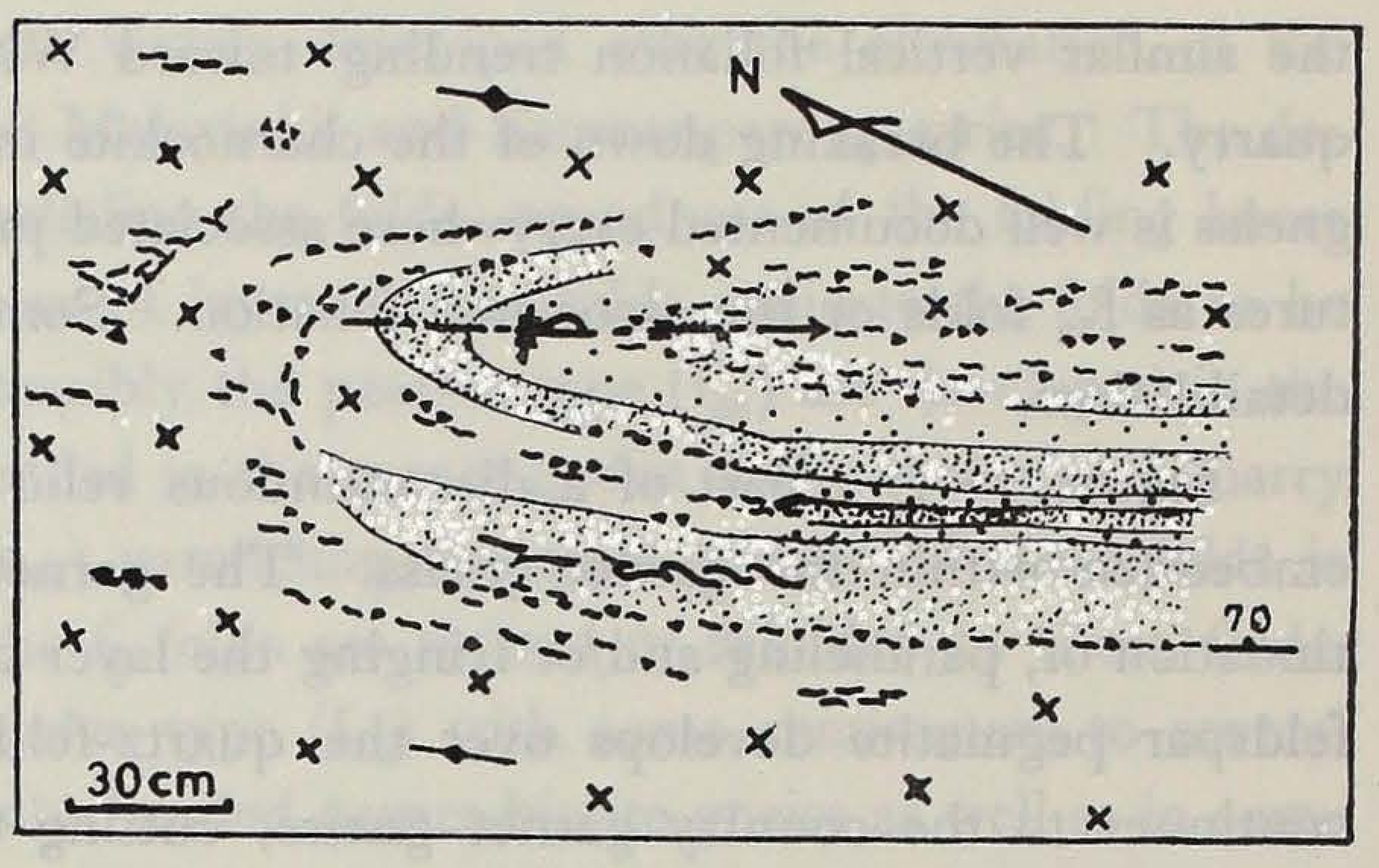

Fig. 17. Folded (f_2) banded charnockite disappearing into the garnet gneiss (southern hill just above the Malayinkil quarry, cf. Figs. 7, 8 and 9) The garnet gneiss represents foliation (s_{3a}) inclined from the axial surface of the fold. Marks are same as in previous figures.

layer on the lower portion of figure 16 suggests the flow of the garnet gneiss and a ductile nature of the unfolded band during this event.

Figure 17 shows the folded (f_2) banded charnockite composed of garnet- and biotite-rich bands and quartz-feldspathic bands disappearing into the garnet gneiss. The garnet-biotite gneiss and garnet- and/or biotite-rich seams adjacent to the charnockite follow the banded and folded structure of the charnockite, indicating their transformation from the mafic-rich band of the charnockite. Away from the charnockite, the foliation (s_{3a}) of the garnet gneiss is inclined from the structures of the charnockite, denoting later posession of the foliation structures of the garnet gneiss than the banded and folded structures of the charnockite.

Figure 18 is a boudinaged block of the banded charnockite embedded in the garnet

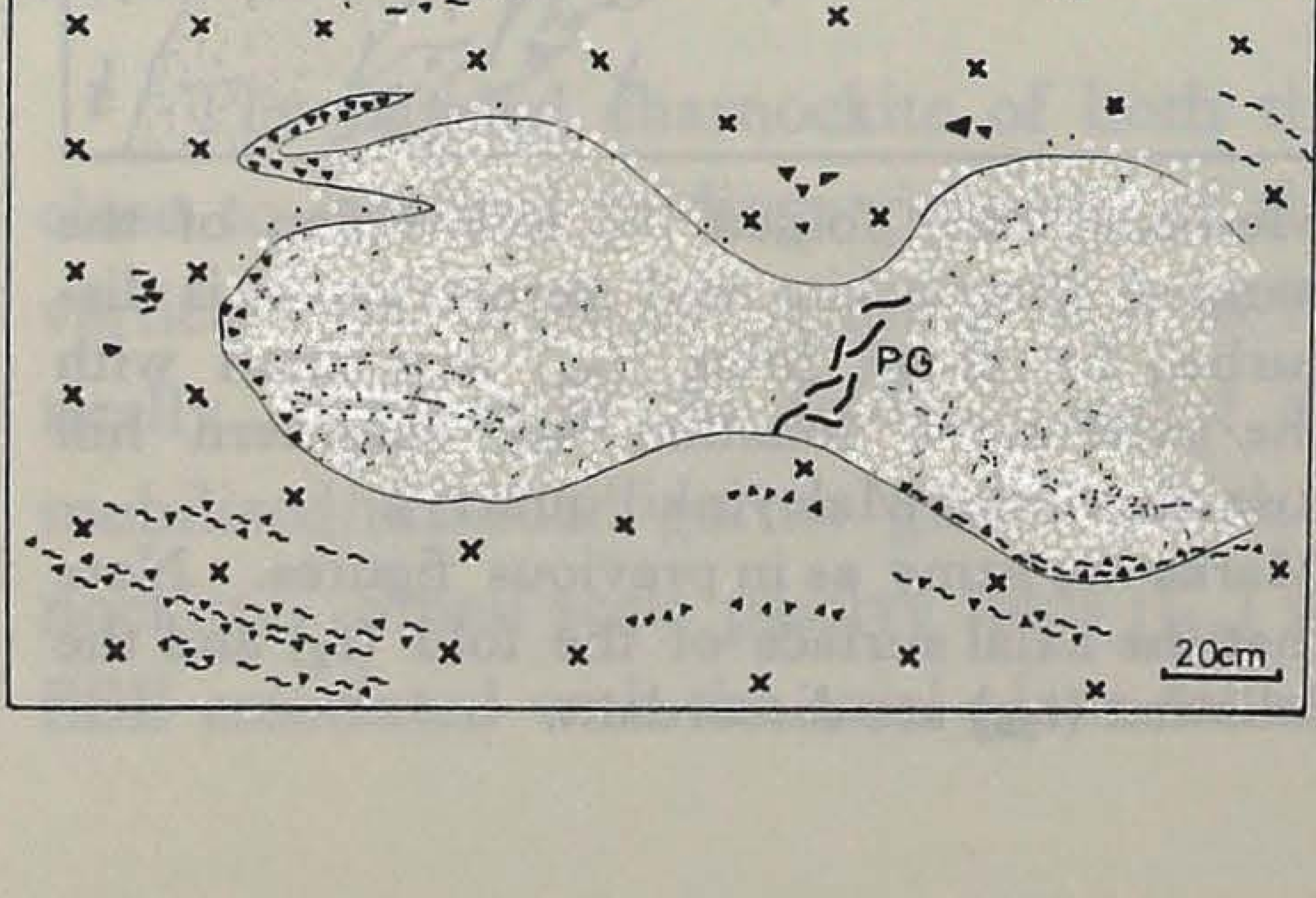

Fig. 18. Boudinaged block of the banded charnockite embedded in the garnet gneiss (southern hill just above the Malayinkil quarry, about 10 meters south of Fig. 17 point). Thick wavy bars (PG): charnockitic biotite pegmatite. Other marks are same as in previous figures. Note that some portions of the garnet gneiss surrounding the boudinaged block are vaguely charnockitic, possibly reflecting the later progressive charnockitization.

gneiss. The pre-existence of quartz-feldspathic bandings (s_1) over the formation of the boudinage structure as well as over the emplacement of the country garnet gneiss, transformation of part of this charnockite into the garnet-biotite gneiss, and a rightward flow of the garnet gneiss at the upper left portion of the boudine are seen.

Microstructures

A specimen No 86011101, collected from the Kunnanpara quarry is a basic charnockite about 50 cm thick interlayered with the garnet gneiss occurring at the southeast wall of the quarry. At the lower half of the wall, the banded charnockite is cut abruptly by the garnet gneiss. This rock provides the characteristic microstructure very poorly affected by the retrogression.

The charnockite layer (s_2) is vertical, striking N60°W, but the trend of the thin banding structure (s_1) in the layer is not well known, some small scale foldings of the thin banding develop locally among the charnockite layer. The surrounding garnet gneiss has somewhat constant and vertical foliation (s_{3a}) striking N70°W and is thus slightly inclined from the trend of the charnockite layer. A thin vein of the charnockitic biotite pegmatite cuts irregularily the charnockite near by the specimen. The rock specimen was collected from the marginal portion of the charnockite layer. It is a dark gray and massive rock at a glance. In some detail, however, a complicated microfold-like structure is seen by tracing vague mafic rich and poor bands of 0.5–1.5 mm thick. A thin section was prepared parallel to the plane striking N44°W and dipping 50°NE, crosscutting the alternation (s_2) and the foliation (s_{3a}).

Under the microscope, the rock is composed mainly of small-grained equigranular polygonal plagioclase and orthopyroxene with a minor amount of clinopyroxene, and a very small amount of biotite. No distinct preferred orientation is discernible; i.e., the rock is generally homogeneous and massive (Fig. 19). The vague banding and microfold structures, however, is very indistinctly indicated by continuation-distribution of pyroxenes. Some orthopyroxenes show a faint tendencey to elongate, possibly parallel to the banding. A faint schistosity is indicated by the roughly parallel arrangement of very fine biotite flakes inclined from the continuation of orthopyroxenes. Its trend appears to be parallel to the foliation of the surrounding garnet gneiss. The biotite is always attached

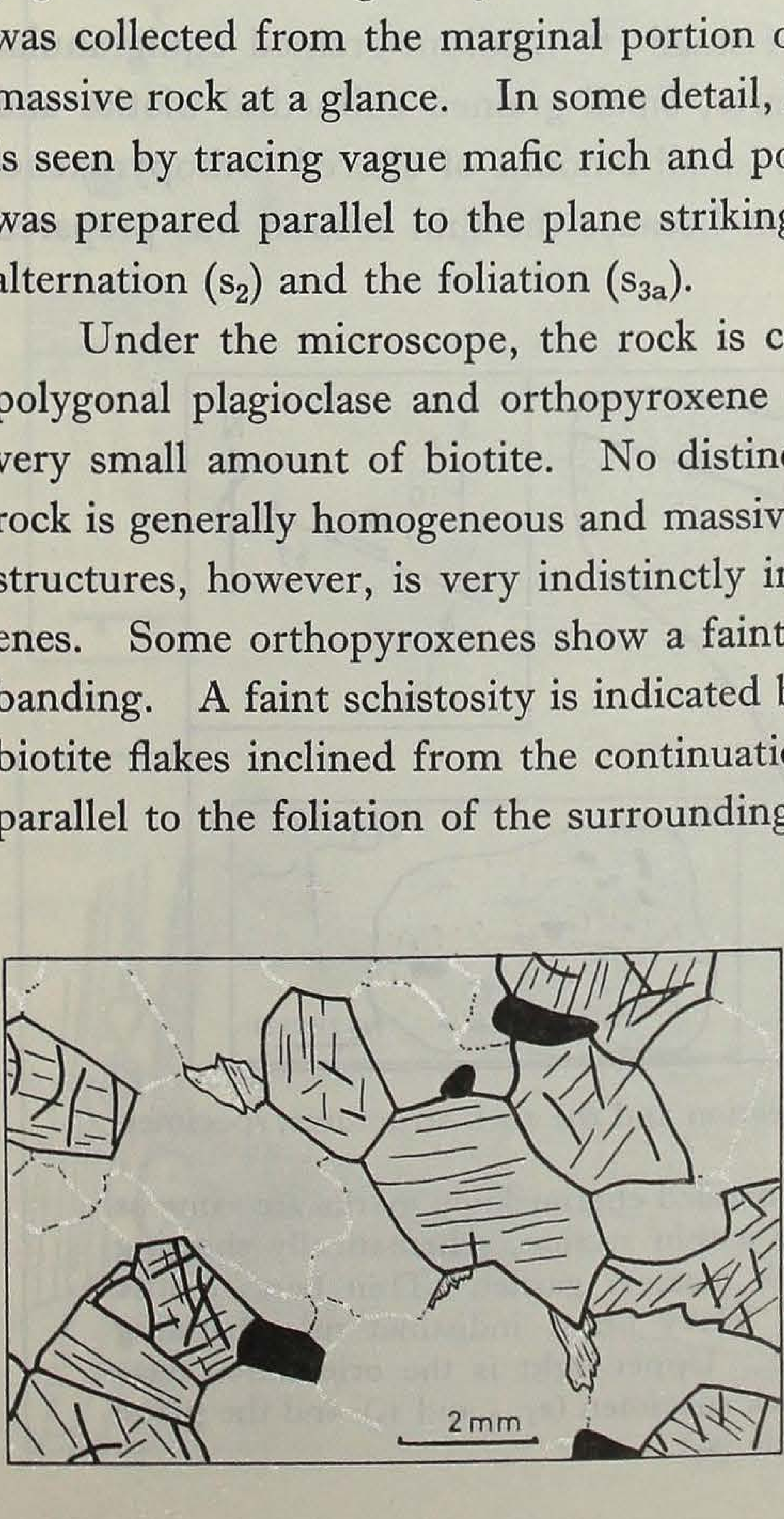

Fig. 19. General microstructure of the basic charnockite, specimen 86011101A. Plagioclase (blank with dotted grain boundaries), orthopyroxene (high relief with cracks and cleavages), opaque minerals (solid), and biotite (moderate relief with thin lines and fine dots). Vague continuation of orthopyroxene is from the upper right to the lower left and younger indistinct schistosity (s_{3a}) trends from the upper left to the lower right as reflected by some biotite flakes.

to orthopyoxene and no embayment is seen over the orthopyroxene at that portion; this occurrence is considered not to conflict with the view that the biotite formed in synchronous with the formation of the foliation in the surrounding garnet gneiss and is much later than the orthopyroxene.

A banded charnockite, specimen No 86010301C, was collected from the Malayinkil quarry, at the crestal portion of an isoclinal fold (f_2) of the alternation (s_2) of layers of the banded charnockite and the garnet gneiss. The crestal portion was disturbed by the later small passive folds (f_{3a}) and associated axial plane foliation-schistosity (s_{3a}), as indicated in Figure 16. The effect of the retrogression event, associated with the development of the biotite schistosity paralleling the foliation of the garnet gneiss, is seen by the microscopic observation of this rock. The rock is dark gray and banded, composed of garnet-biotite charnockite and quartz-feldspathic charnockite. The banding of the rock (s_1, which is parallel to the s_2 alternation) trends N-S and dips 10°E with a lineation plunging 8°SE with faint vertical schistosity (s_{3a}) trending N20°W. A thin section was prepared along the plane with a strike of N67°E and a dip of 71°SE, thus is cut at about right angles to both the banding and schistosity (Fig. 20) and at some tens of degrees inclined from the lineation.

Under the microscope, the rock consists of small- to medium-grained equigranular polygonal to granuloblastic plagioclase and quartz, small-grained subhedral biotite and coarse-grained poikiroblastic garnet, and a very small amount of altered orthopyroxene. No banding structure is seen on the thin section because the thin section was prepared

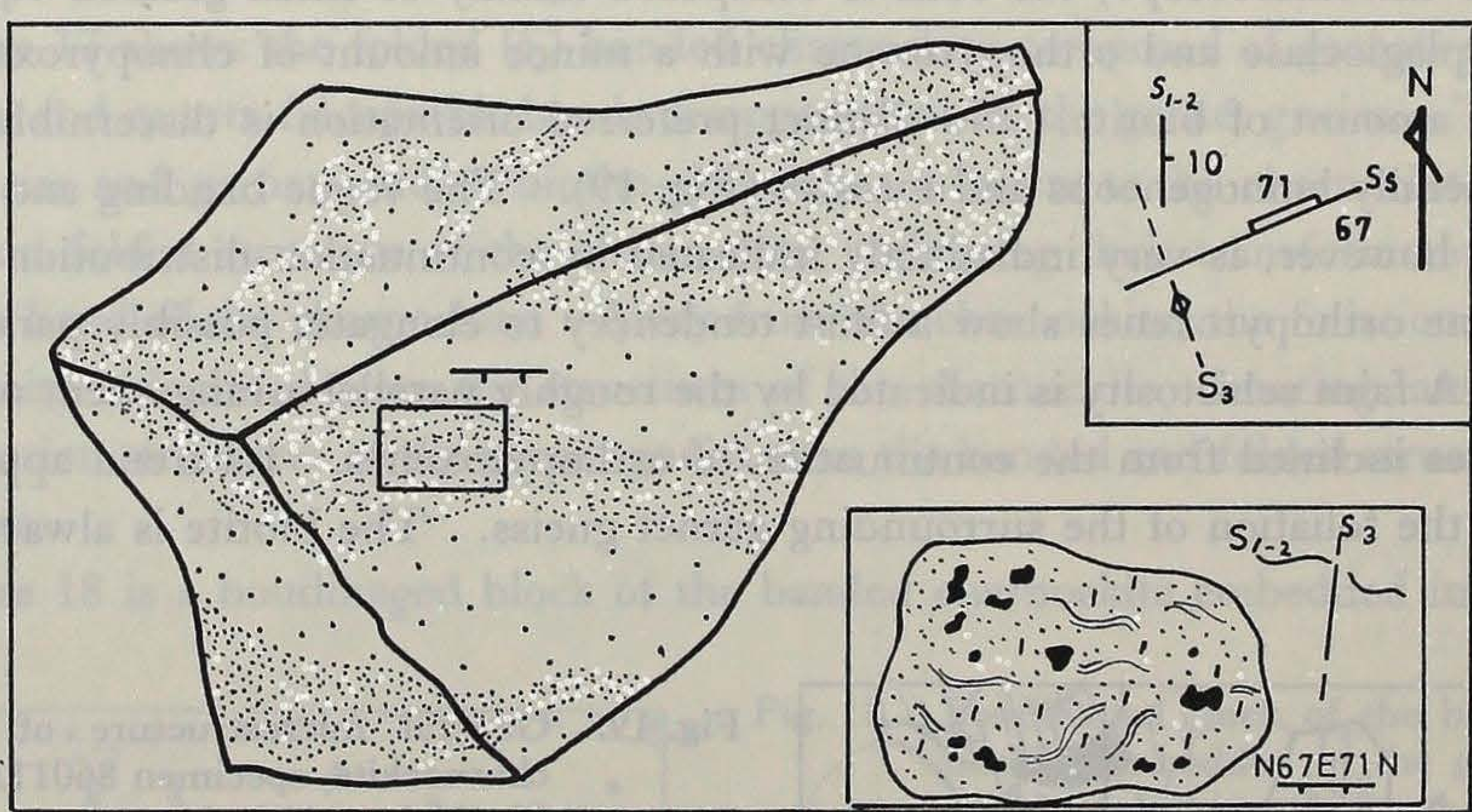

Fig. 20. Orientation relationship of the thin section and the rock structures, specimen 86010301C.
Left figure is a rock specimen of the banded charnockite; marks are same as in previous figures. Lower right is a thin section, schematically showing general structures as follows. Black masses: garnet. Thin bars: biotite flakes, indidating the s_3 structure. Wavy lines: indistinct microbanding structure indicating the s_{1-2} structure. Upper right is the orientation relationship between structures of the rock specimen (s_{1-2} and s_3) and the plane along which the thin section was made (s_s).

from somewhat homogeneous portion of the rock. However, sporadic continued distribution of relatively coarse-grained biotite parallels the banding of the rock. Younger schistosity (s_{3a}) is indicated by roughly parallel arrangement of the basal plane of some biotites. Small-grained plagioclase is polygonal to granular with straight to curved grain boundaries. But medium-grained plagioclase is robate and includes fine-grained granular quartz and rarely, a part of biotite, thus bearing the porphyroblastic characteristics (Fig. 21). Small- to medium-grained quartz has generally robate boundaries, although straight boundaries are sometimes found. Fine-grained quartz is rounded to subrounded, either being included in the medium-grained plagioclase or embedded at the grain boundaries of plagioclases. Biotite nearby or attached to garnet or orthopyroxene is partly "myrmekitic" with quartz suggesting some reaction between them (Fig. 22), possibly the formation of

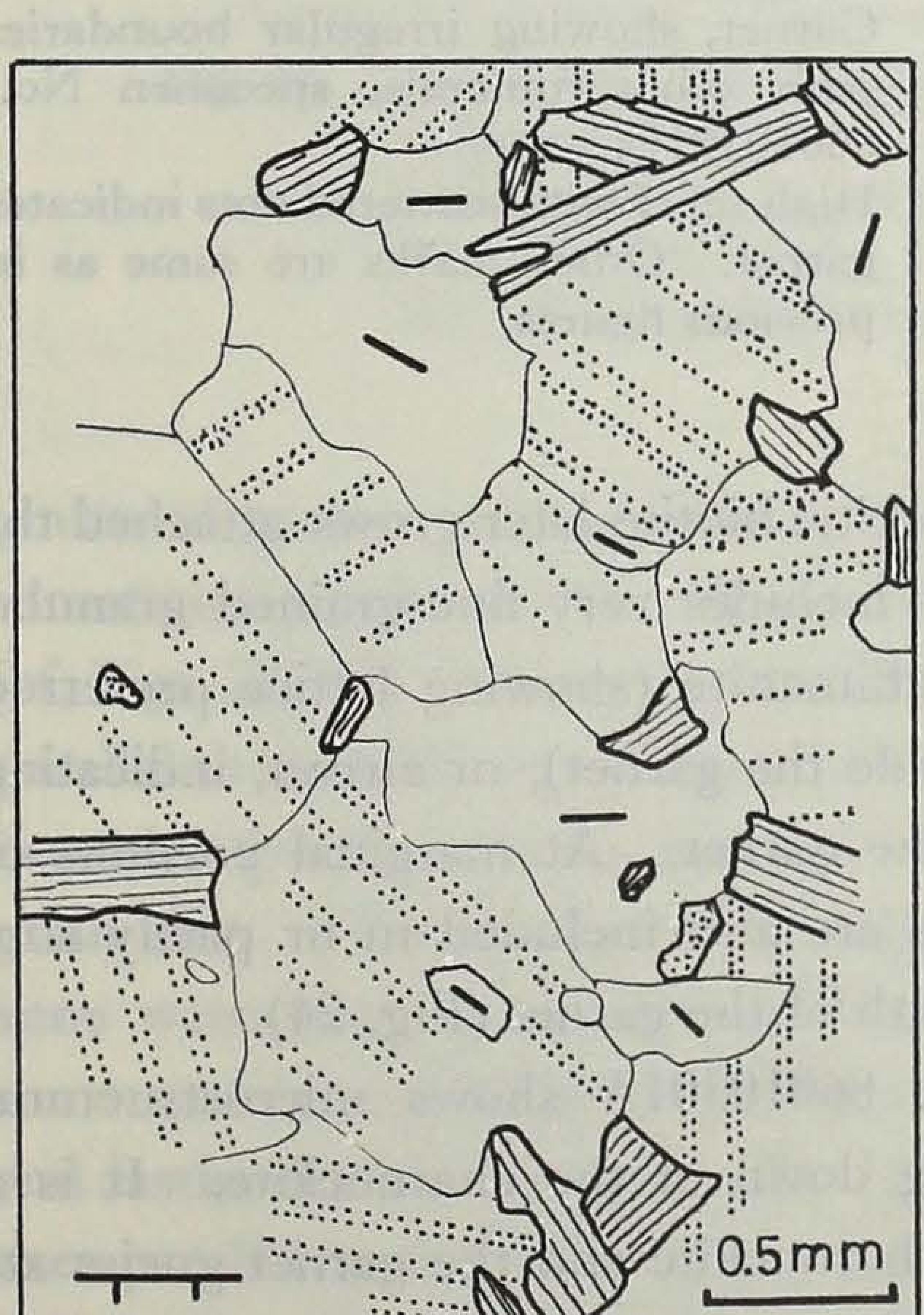

Fig. 21. Microstructures of salic minerals of the garnet-biotite charnockite, Specimen 86010301C. Plagioclase: dotted stribes, quartz: blank with a bar which indicates the orientation of the plane in which C axis lies, and biotite: high relief with cleavages. An orientation mark (lower left) is the same one as in Fig. 20.

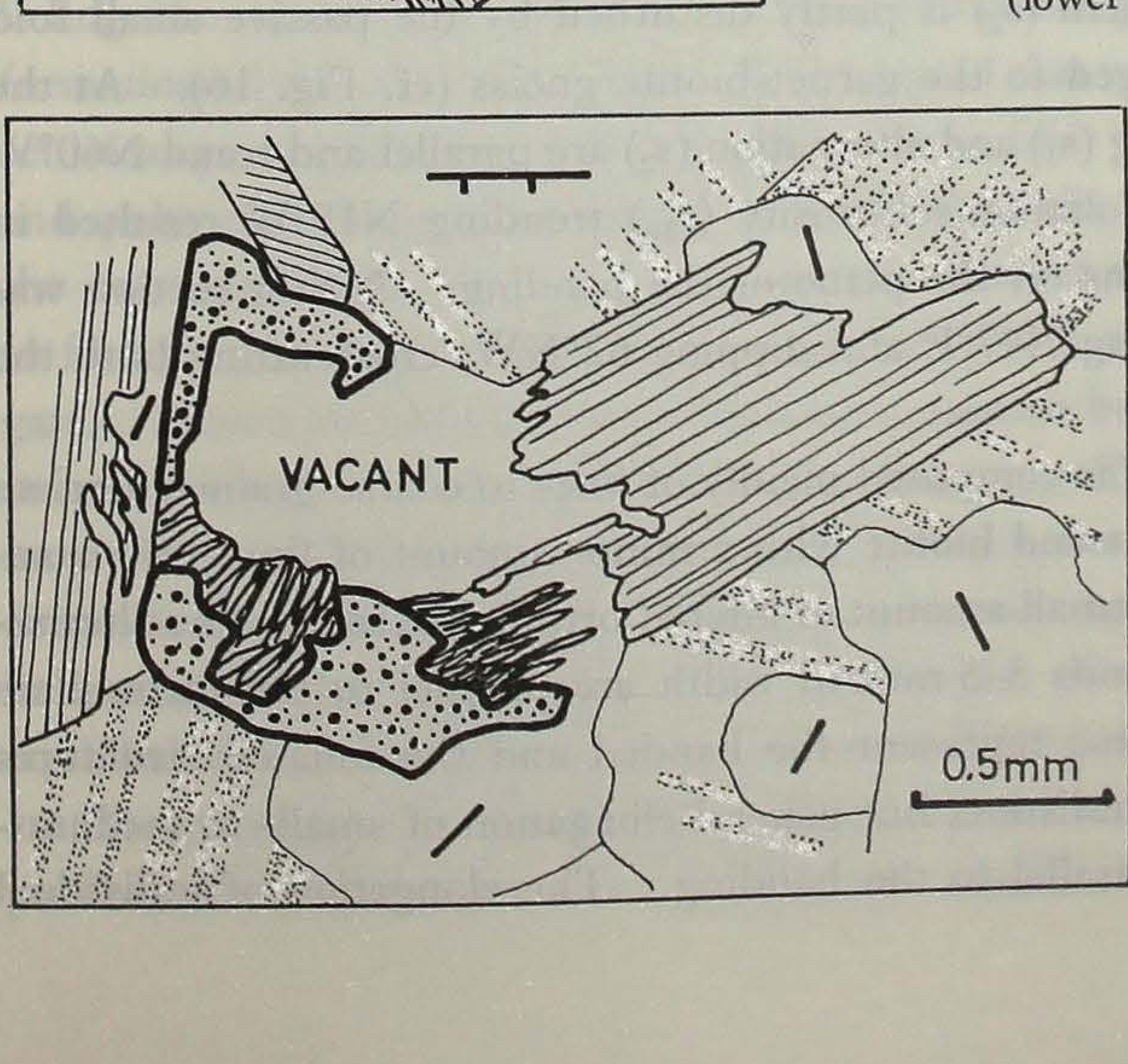

Fig. 22. Later growth of "myrmekitic" aggregate of biotite attached to orthopyroxene, specimen 86010301C. Orthopyroxene is now changed completely to aggregates of smectite (high relief with dots) and biotite (thin and fine cleavage lines).

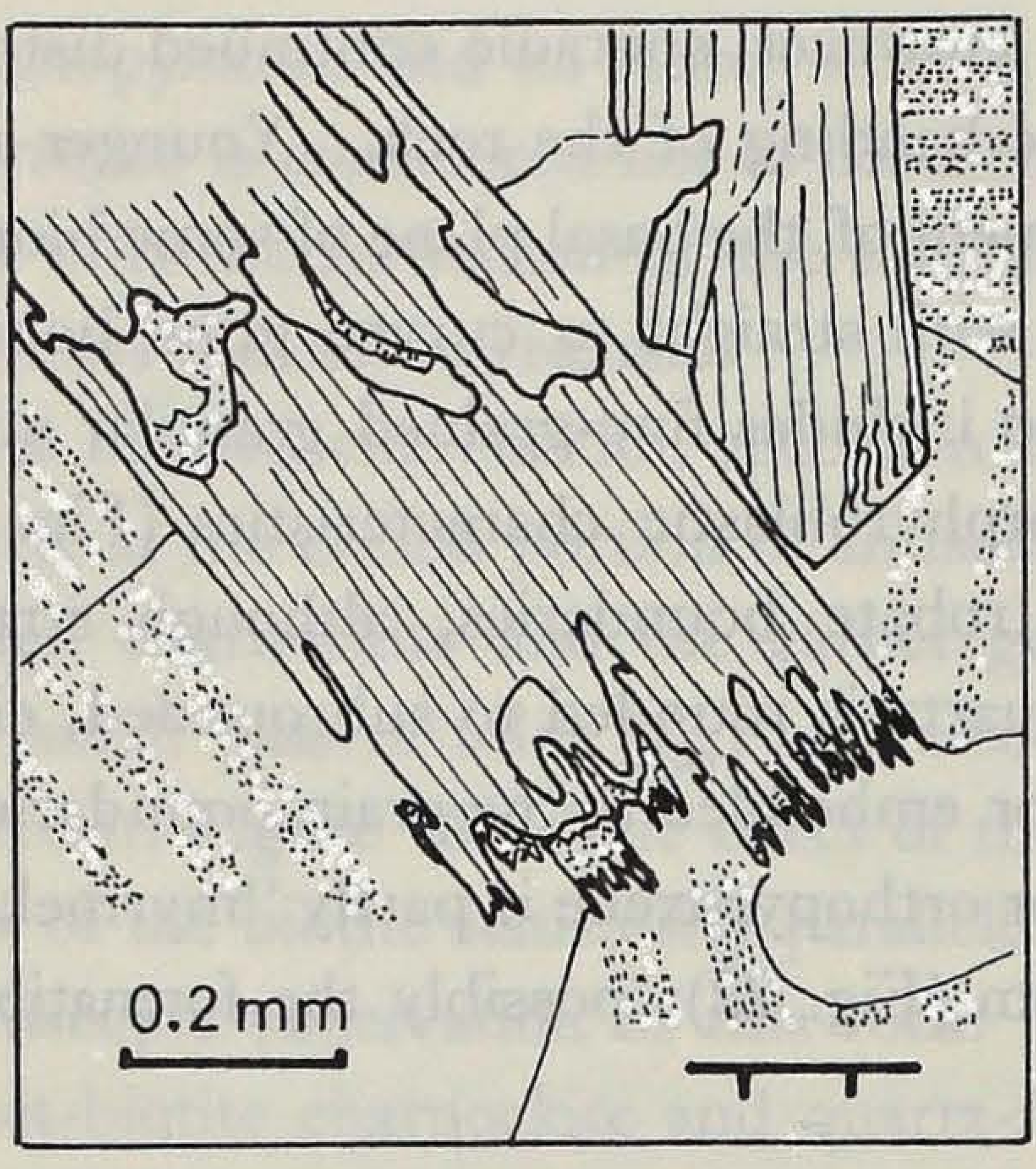

Fig. 23. Later growth of very fine "myrmekitic" biotite (dotted) at the edge of the pre-existent biotite flake, specimen No. 86010301C.
Marks are same as in previous figures.

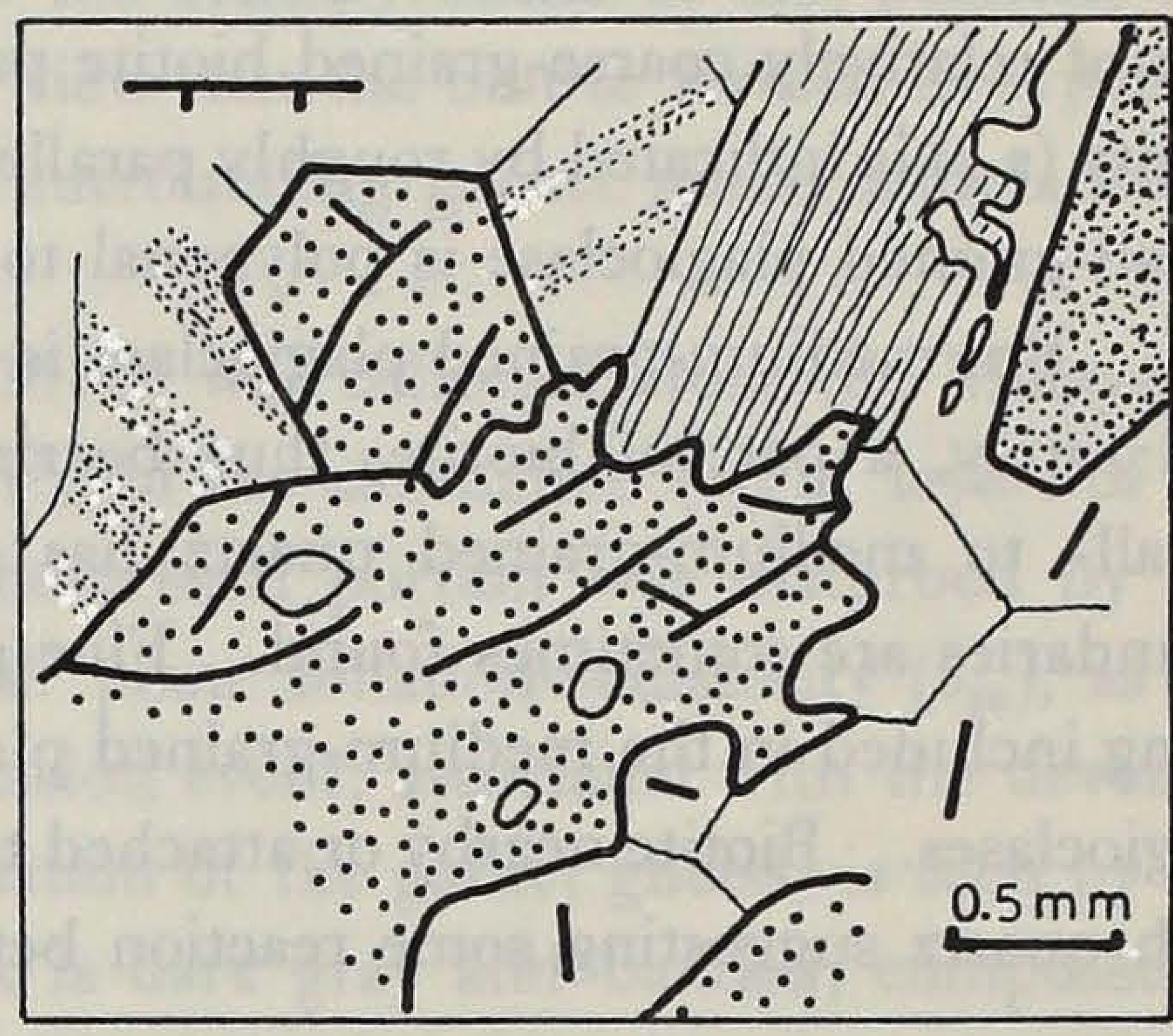

Fig. 24. Garnet, showing irregular boundaries with other minerals, specimen No. 86010301C.
High relief with scattered dots indicates garnet. Other marks are same as in previous figures.

the former from the latter two minerals. Fine myrmekitic biotite later grows attached the edge of ordinary biotite (Fig. 23). Garnet generally includes very fine-grained granular biotite and quartz, and rarely plagioclase, apatite, sillimanite (showing lattice preferred orientation inclined from banding or schistosity outside the garnet), or zircon, indicating the pre-existence of these xenocrystic minerals to the garnet. At marginal portions of garnet, small-grained quartz, plagioclase, and biotite are also included in or partly surrounded by the garnet, indicating the prolonged growth of the garnet (Fig. 24).

A specimen from the Malayinkil quarry, No. 86010301A shows microstructural changes of a further advanced stage of the breaking down of the charnockite. It is a garnet-biotite gneiss embeded between the banded charnockite and the garnet gneiss attached. The boundary between them (s_2) is partly disturbed by the passive small fold (f_{3a}) where the charnockite is changed to the garnet-biotite gneiss (cf. Fig. 16). At the portion of the specimen, the banding (s_1) and alternation (s_2) are parallel and trend N60°W and dip 50°NE. A faint vertical foliation/schistosity (s_{3a}) trending N15°W resulted in the mineral and undulation lineations on the plane of the banding. A thin section was prepared parallel to the plane striking N47°E and dipping 62°NW, crosscutting both the banding and schistosity (Fig. 25).

Under the microscope, the rock is composed mainly of fine- to coarse-grained serriate amoeboed quartz, plagioclase, garnet and biotite with a minor amount of fine- to coarse-grained opaque minerals and a very small amount of altered orthopyroxene. The alternation of mafic-rich and salic-rich bands 3–5 mm in width are parallel to the incomplete lensoidal distribution of garnet; these represent the banded and the foliated structures (parallel to s_1 and s_2) of the rock. Indistinct but general elongation of small- to medium-grained quartz and plagioclase is parallel to the banding. The elongation of individual

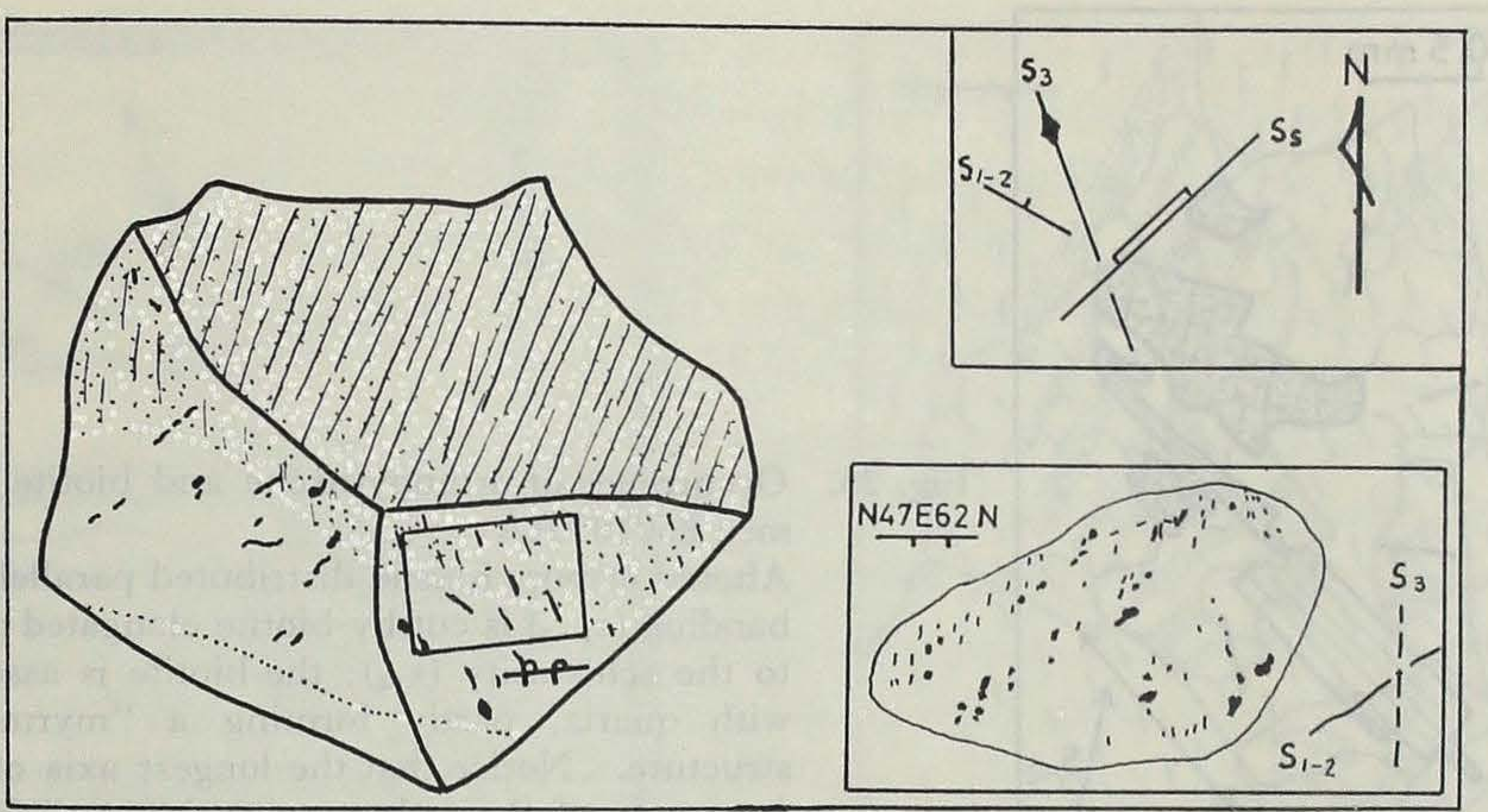

Fig. 25. Orientation relationship of the thin section and the rock structure, specimen 86010301A.
Marks are same as in Figure 20. The plane of the section on the rock specimen is N47°E 62°SE, but the thin section itself was prepared to see from NW, thus parallel to the plane N47°E 62°NW.

grains of garnet, orthopyroxene, coarse-grained quartz, biotite, and opaque minerals is sometimes parallel to the schistosity (s_{3a}) of the rock and thus inclined from the banding (cf. Figs. 25, 26). The scattered distribution of garnet as well as orthopyroxene, however, is parallel to the banding as if indicating that pre-existent large grains were disrupted. Spaces between the scattered graines are occupied by quartz, feldspars and biotite of various grain size. These occurrences suggest that the pre-existent large garnet and orthopyroxene were fragmented and distributed parallel to the banding/foliation planes and later, some quartz and feldspars filling the spaces between the fragments have recrystallized, and lastly, during the schistosity epoch, the fragments were rotated to arrange their long axes parallel to the schistosity. The elongation of biotite and coarse-grained quartz paralleling the schistosity may indicate the syntectonic growth of these minerals during the formation of the schistosity (s_{3a}). It is noticed that some biotites elongated paralleling the schistosity cut orthopyroxene (Fig. 26). Some fine- to small-grained plagioclase is equant and polygonal, being paleozomic in contrast to the porphyroblastic neozomic nature of the coarse-grained plagioclase and quartz. Garnet is poikiroblastic, including very fine- to fine-grained and rounded to subrounded quartz and rarely, plagioclase or their aggregate. Almost all orthopyroxene alter into greenish brown clayii material which is possibly smectite because of its uniaxial positive nature. This alteration is considered to be a much later event, because no recrystallization is seen over the smectite and no tectonic event is associated with it. Garnet is generally surrounded by or attached to biotite, indicating the later formation of at least a part of the biotite than the garnet, and the equilibrious coexistence of the two minerals during the later period.

A specimen No. 86010301B, collected from the Malayinkil quarry, is a mobilized portion of the garnet gneiss within which a schlieric layers of the banded charnockite,

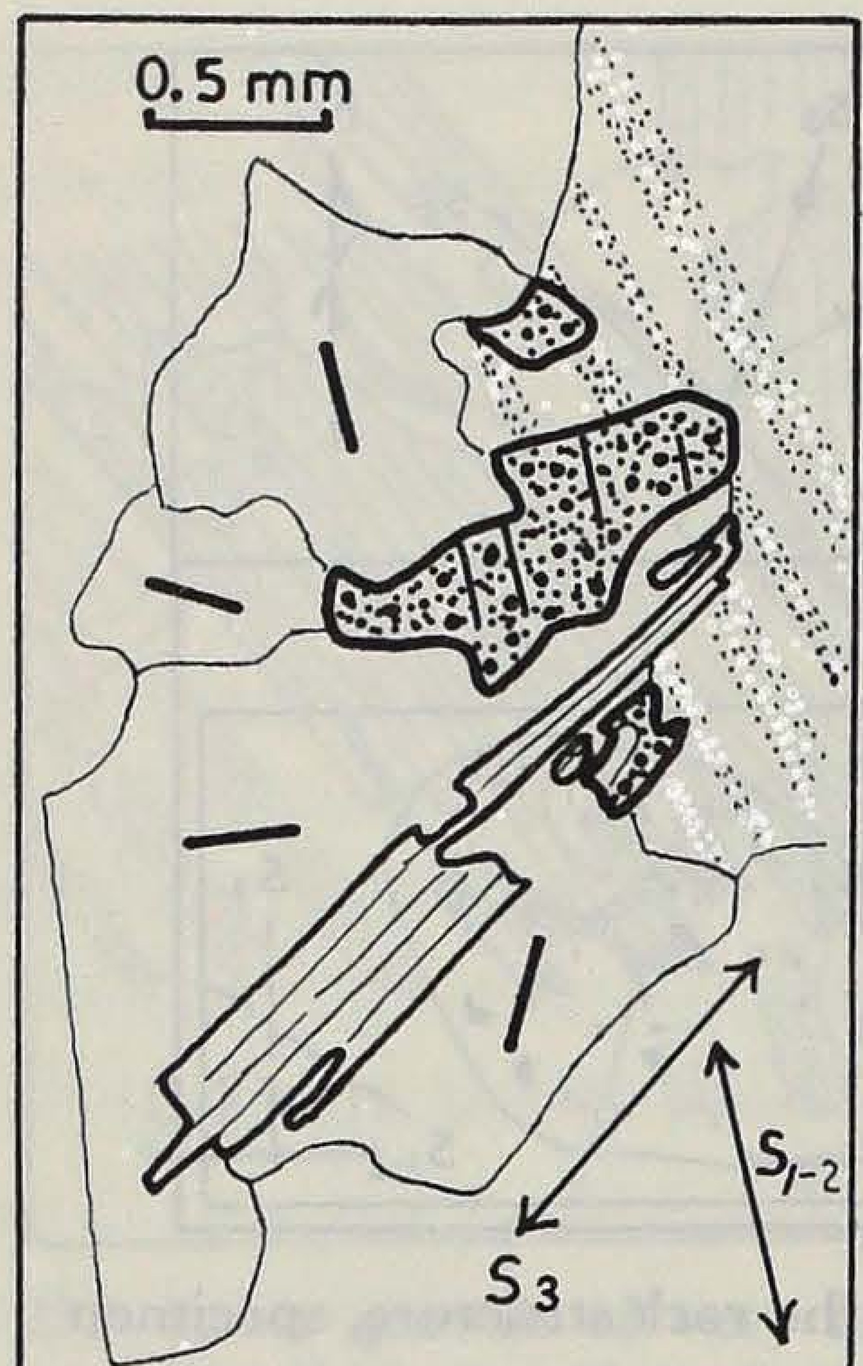

Fig. 26. Occurrence of orthopyroxene and biotite, specimen 86010301A.
Altered orthopyroxene distributed parallel to the banding (s_{1-2}) is cut by biotite elongated parallel to the schistosity (s_{3a}); the biotite is associated with quartz, partly forming a "myrmekitic" structure. Notice that the longest axis of some fragments of the orthopyroxen is parallel to the schistosity. Other marks are same as in previous figures.

which is partly changed to the garnet-biotite gneiss, is embedded. The microscopic observation of this rock shows the development of a coarse-grained neozomic pegmatitic facies over a fine-grained relic gneissic facies. The charnockite layer (s_2) trends WNW-ESE and dips moderately north, with an isoclinally to tightly folded structure (f_2) near the specimen. Foliation (s_3) of the garnet gneiss is vertical with a NNW-SSE strike (cf. Fig. 16). The thin section was prepared at a relatively homogeneous portion of the garnet gneiss about 20 cm apart from the schlieric layer. The plane of the slide strikes N80°E and dips 25°S, thus crosscutting both the banding and foliation (Fig. 27). The thin section is mostly massive, pegmatitic, and quartz-feldspathic. Only a very small portion of the slide is small-grained and gneissic where the continuation and scattered distribution of biotites exhibit the foliation structure (cf. Fig. 27). The boundary of the gneissic facies, as well as the foliation observed on the slide are roughly parallel to the orientation of the nearby schlieric charnockite/garnet-biotite gneiss layer.

Under the microscope, the pegmatitic facies is composed of small- to very coarse-grained inequigranular quartz and perthite, with minor amounts of myrmekitic plagioclase, biotite, muscovite, and hydromica. Medium- to coarse-grained quartz and potash feldspar are porphyroblastic, including or robating into the relic small-grained myrmekitic plagioclase (Fig. 28). Fine-to small-grained granular quartz, small-grained biotite and muscovite and intergranular albite develop at the grain boundary of potash feldspar. Veins and irregular aggregates of hydromica cut all the other minerals. Small subhedral biotites are distributed at grain boundaries of potash feldspars. Lines of aggregates of very fine-grained opaque minerals sometimes demarcate the outer margin of biotite, and an aggregate of very fine and thin grains of biotite (fine "myrmekitic" biotite) is attached outward from it, indicating the later formation of the fine myrmekitic biotite than the other biotites. Muscovite is attached with biotite or fills the cleavage-parallel cracks of biotite. The gneissic facies is mainly composed of fine- to medium-grained plagioclase

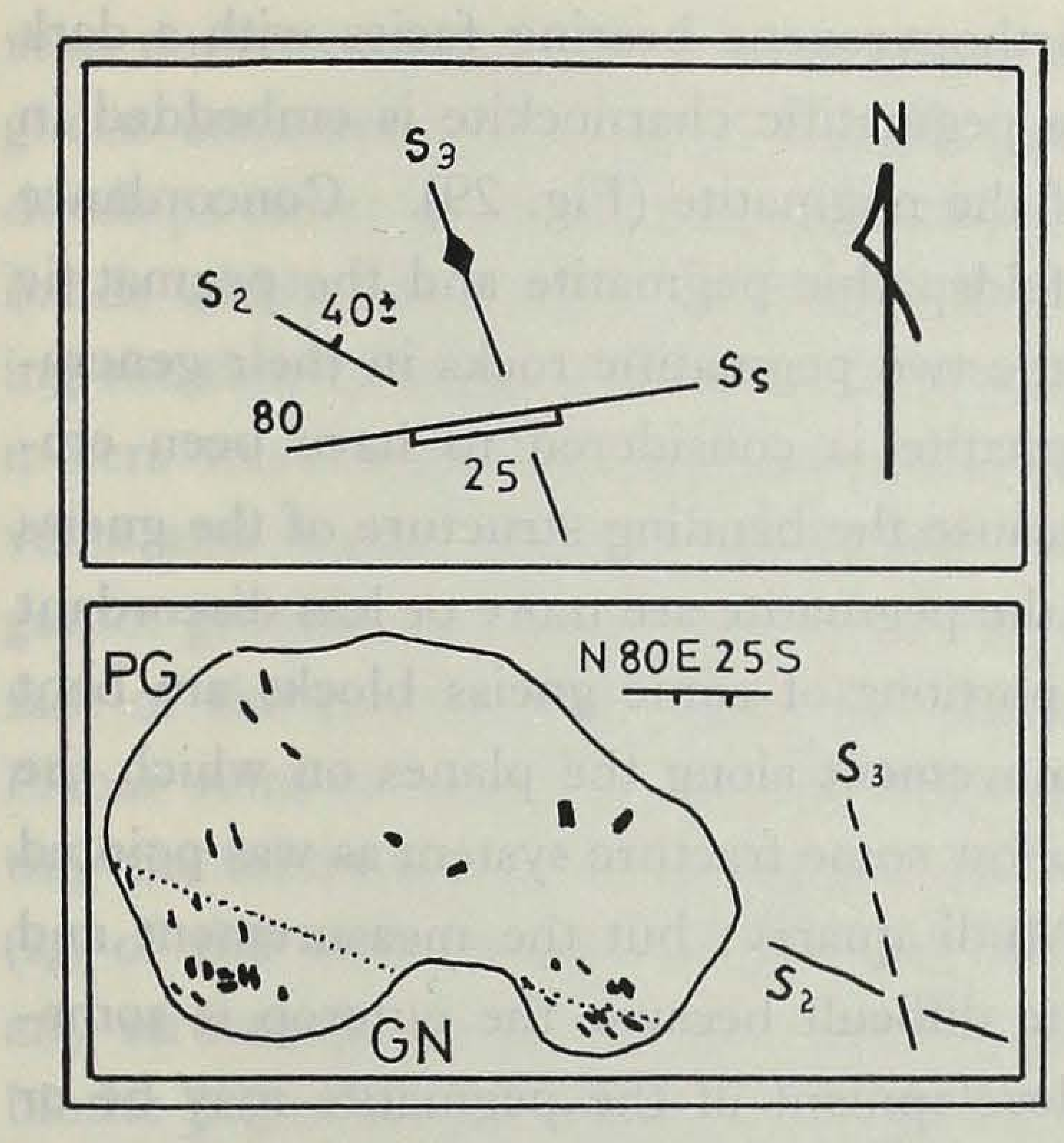

Fig. 27. Orientation relationship between the thin section and the rock structure, specimen 86010301B.
Solid mass is biotite. Other marks are same as in Fig. 20. The upper portion (PG) of the slide is pegmatitic and the lower portion (GN) is gneissic (see text).

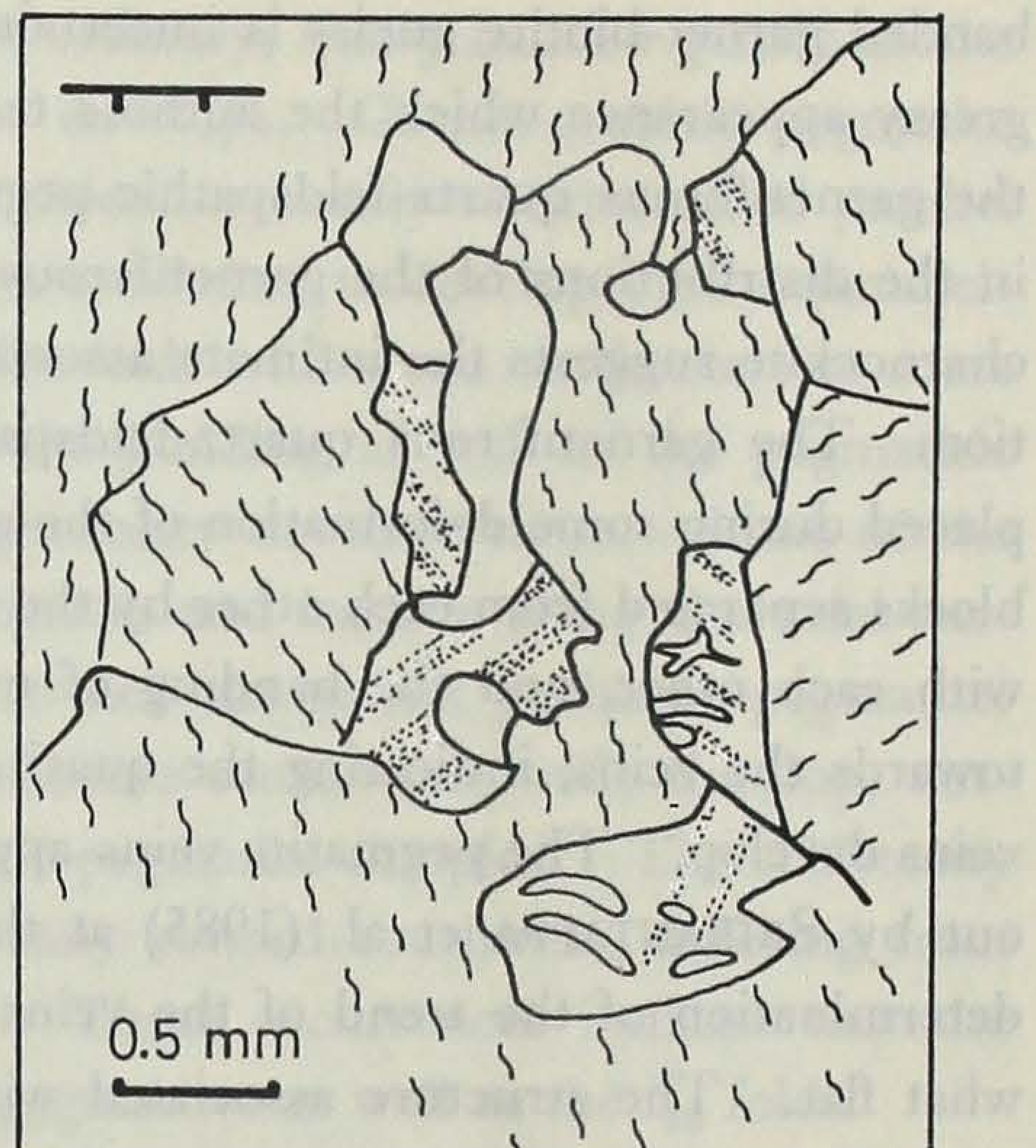

Fig. 28. Microstructure of salic minerals, specimen 86010301B.
Large potash feldspars (wavy bars) appear to have formed consuming smaller-grained plagioclases with myrmekitic texture. Small-grained quartzes are also relics. Marks are same as in previous figures.

and biotite with a lesser amount of quartz. Fine-grained potash feldspar and plagioclase are polygonal and small- to medium-grained plagioclase and potash feldspar are robate to porphyroblatsic over the fine-grained polygonal ones. Very fine-grained quartzes occur in some plagioclases and potash feldspars. Biotites form deccussate aggregates showing foliation. At the edge of a grain of biotite, "myrmekitic biotite" develops associated with leucoxenic aggregates.

BRIEF SURVEY ON THE PROGRESSIVE CHARNOCKITIZATION

Evidence of the progressive charnockitization from southern Kerala including the present area has already been reported by Srikantappa et al. (1985). In the following, a brief survey on the field occurrence of the progressive charnockitization from the view point of the chronologic relationship with the breaking down of charnockite will be mentioned.

The pegmatitic charnockite under the progressive formation from the garnet-biotite gneiss was observed at the Mannantala quarry. The thinly banded garnet-biotite gneiss is traversed by veins of garnet-quartz-feldspar pegmatite, representing totally the diktyonite migmatite. This pegmatite is termed the garnetiferous quartz-feldspathic pegmatite. The relationship between the garnetiferous quartz-feldspathic pegmatite of this outcrop and the garnet gneissose pegmatite occurring at a nearby outcrop of the thinly banded garnet-biotite gneiss is uncertain. An orthopyroxene bearing facies with a dark greasy appearance which the authors termed the pegmatitic charnockite is embedded in the garnetiferous quartz-feldspathic pegmatite of the migmatite (Fig. 29). Concordance in the distributions of the garnetiferous quartz-feldspathic pegmatite and the pegmatitic charnockite suggests the intimate association of the two pegmatitic rocks in their generation. The garnetiferous quartz-feldspathic pegmatite is considered to have been emplaced during some deformation of the gneiss because the banding structure of the gneiss blocks separated from each other by the veins of the pegmatite are more or less discordant with each other, and the banding of marginal portions of some gneiss blocks are bent towards the veins, indicating the quasi ductile movement along the planes on which the veins develop. The pegmatite veins appear to follow some fracture system as was pointed out by SRIKANTAPPA et al. (1985) at the Pon Mudi quarry; but the measurement and determination of the trend of the veins are quite difficult because the outcrop is somewhat flat. The structure associated with the development of the pegmatite may be or may not be referred to the passive folds (f_{3_b}) widely developed in the same quarry. This point should be further studied in future.

The occurrence of the pegmatitic charnockite becomes less and finally can not be

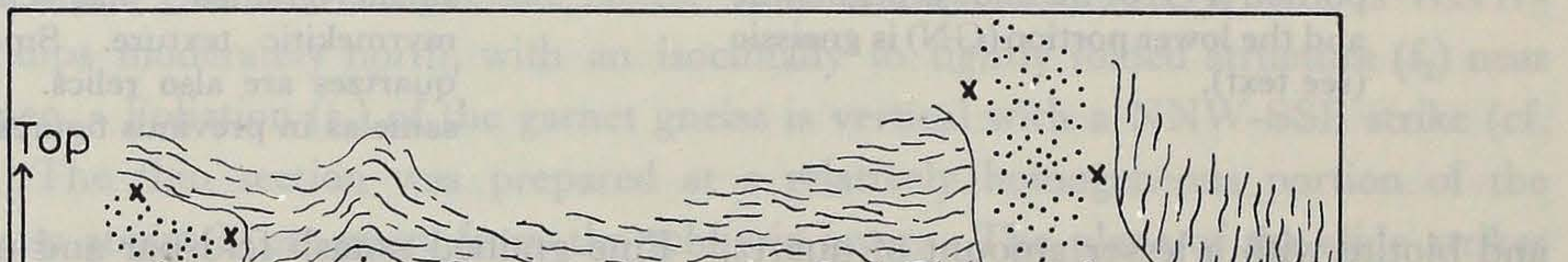

Fig. 29. Pegmatitic charnockite later formed, cutting the thinly banded garnet-biotite gneiss (Mannantala quarry). The garnetiferous quartz-feldspathic pegmatite and the pegmatitic charnockite cut discordantly the thinly banded garnet-biotite gneiss.

seen northwestward in the same quarry where the ordinary, thinly banded garnet-biotite gneiss sometimes with open to close passive fold develops. Garnet-granitic pegmatite develops either as vaguely circumscribed pools or veins, or clearly circumscribed parallel bands within the gneiss. Flattened clots of quartz are found to develop partly, paralleling the thin banding structure. Mesoscopic passive folds with some centimeters to some meters wavelength (f_{3b}) are dominant and affect the banding as well as the pegmatitic veins and bands, and the axial plane foliation-schistosity develops there. Some of the garnet granitic pegmatite come to crosscut the gneisses and intrude along the axial surface of the passive fold where the pegmatite is termed the garnet gneissose pegmatite. Planar veins of weak schistose biotite pegmatite of some centimeters wide develop, cutting the folded garnet-biotite gneiss - garnet granitic pegmatite complex. The schistosity (s_4) of the vein trends NW-SE and dips moderately toward southwest, differing from any structures of the country gneisses (Fig. 30). These occurrences indicate that the biotite pegmatite postdates all the garnet bearing pegmatites as well as the f_{3b} folds.

At the Malayinkil quarry where the breaking of charnockite is observed, a faint indication of the making of charnockite is also observed (Fig. 31). At the northeastern corner of this quarry, a layer of the garnet gneiss of about 30 cm wide is interbedded between layers of the banded garnet-biotite charnockite. The heterogeneous garnet-biotite gneiss develops at some boundaries between the charnockite and the garnet gneiss. Foliation of the garnet gneiss composed of lensoidal aggregates of garnet and/or biotite is parallel to the interbedded structure. A portion with varying width of 10 to 30 cm wide showing

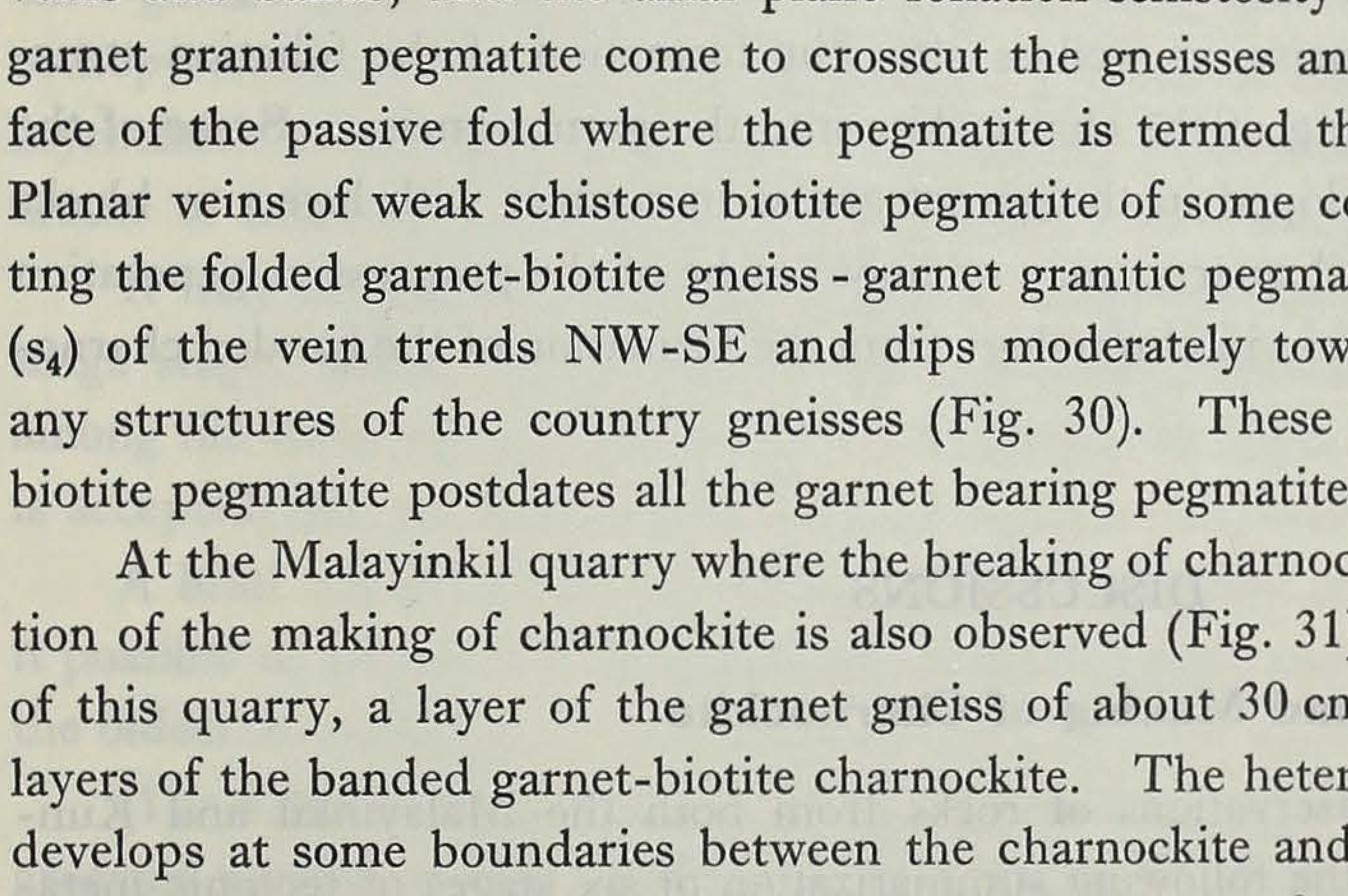

Fig. 30. Later biotite pegmatite and new schistosity (Manantala quarry).
The migmatitic thinly banded garnet-biotite gneiss with garnet granitic pools and with dominant passive folds (wavy bars) is cut by the biotite pegmatite (thick bars). The thick bar indicates schematically single crystals of biotite, which represent the new schistosity (s_4).

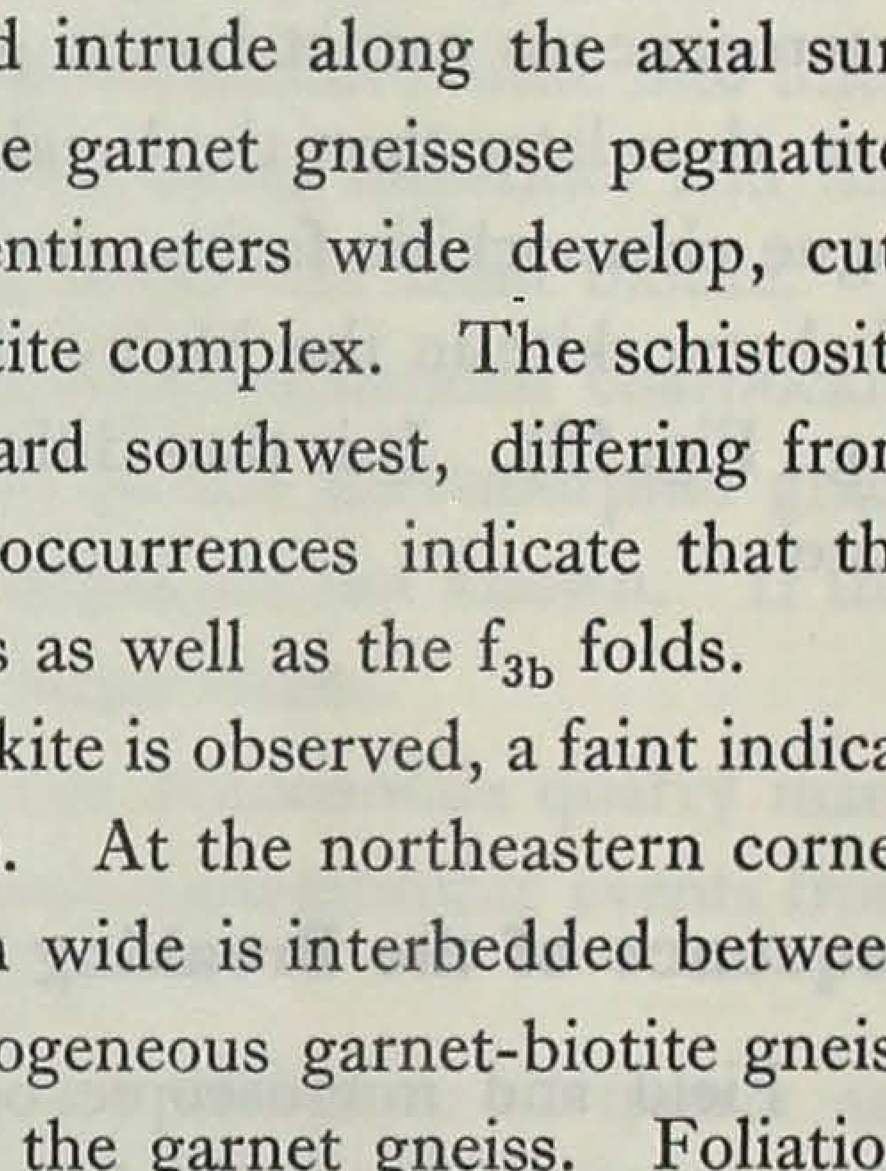

Fig. 31. Pegmatitic charnockite developed over the garnet gneiss (northern part of the eastern cliff of the Malayinkil quarry).
Scattered dots (CP): pegmatitic charnockite, partly overlapped by the charnockitic biotite pegmatite (thick bars). Other marks are same as in previous figures.

dark and greasy appearance characteristics of the pegmatitic charnockite traverses the layer of the garnet gneiss. A biotite pegmatite with greasy appearance (charnockitic biotite pegmatite) is associated with the pegmatitic charnockite. The charnockitic biotite pegmatite cuts the interbedded garnet gneiss/banded charnockite outside the garnet gneiss layer. No indication of disturbance of the charnockitic rocks by the foliation tectonics is obsereved. The mode of occurrence of the pegmatitic charnockite above mentioned indicates the later formation of this rock after the formation of both the garnet gneiss and heterogeneous garnet-biotite gneiss, as well as after the formation of the foliation structure, thus later than the breaking of the charnockite into the garnet gneiss. Some of the vague charnockitic facies, developed in the garnet gneiss in contact with layers or blocks of charnockite in the Malayinkil quarry, may or may not be of the progressive generation (e.g., Fig. 18). It is thus different in chronology from the formation of the banded charnockite.

DISCUSSIONS

Sequence of the Breaking and Making of Charnockite

Field and microscopic observations of rocks from both the Malayinkil and Kunnanpara quarries may lead to the following summarization of six stages of tectonic-metamorphic events as follows from the oldest to youngest (Fig. 32).

(1) An alternated sequence of rocks existed, which includes intrafolially folded (f_1) banded rocks (original rocks of the banded charnockite) and quartz-feldspathic rocks (original rocks of the garnet gneiss). (2) Flexural slip folds of the tight to isoclinal type (f_2) affected the alternated sequence. A strong flattening affected the rock during this tectonics resulting in the disrupted distribution of garnet and orthopyroxene and the indistinct dimensional preferred orientation of small- to medium-grained quartz and feldspars. All of these minerals are now seen as relic minerals or earlier structures in some banded charnockite. (3) Small-grained polygonal plagioclase, orthopyroxene, quartz, and potash feldspar recrystallized under static conditions, and resulted in the annealing polygonal structure. Some garnets are also considered to have recrystallized during this stage. These minerals and structures are typically seen in the banded charnockite, or seen as relics in all other rocks. (4) A part of the banded charnockite is transformed into the garnet gneiss through the garnet-biotite gneiss in association with the formation of foliation-schistosity structures (s_{3a}) paralleling the axial surface of the NW-SE passive folds (f_{3a}). The quartz-feldspathic charnockite more or less selectively changed to the garnet gneiss during this event. The lotation of pre-existent fragments of garnet, orthopyroxene, and possibly, all other minerals, the recrystallization of a part of quartz and biotite which are elongated paralleling the foliation, and the development of biotite replacing both garnet and orthopyroxene, are all the microstructural events during this stage. During a later period of this stage, a part of the garnet gneiss was more or less mobilized to form the garnet gneissose pegmatite, a part of which moved, cutting all pre-

vious structures, intruding nearly parallel to the axial surface of the f_{3a} fold. Porphyroblastic coarsening of quartz, feldspars, and garnet over the small-grained polygonal quartz and feldspars as well as recrystallization of some biotite, all being typically seen in the garnet gneiss, but incipiently found in many other rock types, are considered to have taken place during this later period. (5) Charnockitic biotite pegmatite and the pegmatitic charnockite developed randomly, cutting the banded charnockite and the charnockite-garnet gneiss alternations. (6) Much later stage or stages include; alteration of orthopyroxene into smectite, transformation of a part of the pre-existent biotite into finely myrmekitic biotite aggregate, faint development of hydromica along indistinct and thin cracks of minerals and grain boundaries, and formation of muscovite from biotite.

It may be possible to collect stages 1–3 into one, as the folded banded charnockite mega stage, because there appears to be a small difference in the metamorphic grade among the three stages and the time span among the three stages are not known. If this is accepted, the six stages above may be decreased to four mega stages.

A brief survey on the progressive charnockitization at the Mannantala quarry made it possible to summarize the following sequense of four tectonic-metamorphic events from the oldest to youngest.

(1) Thinly banded garnet-biotite gneiss with a flattened structure of quartz aggregates paralleling the banding existed possibly with the already formed garnet granitic pegmatite. (2) Passive folds (f_{3b}) and associated axial plane foliation formed. A part of the garnet granitic pegmatite mobilized and intruded to form the garnet gneissose pegmatite. The trend of the intrusion as well as the foliation of the garnet gneissose pegmatite is parallel to the axial surface of the f_{3b} passive folds. (3) Quasi ductile deformation, to form some fracture system, and development of veins of garnetiferous quartz-feldspathic pegmatite were associated with the pegmatitic charnockite. (4) The biotite pegmatite intruded, and new NW-SE schistosity developed over it.

Comparing the tectonic-metamorphic events of the two examples discussed above (Fig. 32), those events surrounding and before the formation of the pegmatitic charnockite including the f_3 folds and the mobilization of the gneissose pegmatite are quite analogous. The tectonic event, during which the banded structure and flattened quartz of the thinly banded garnet-biotite gneiss of the Mannantala quarry were formed, may be compared either with the f_1 or the f_2 folding events of the Malayinkil and Kunnanpara quarries. Absence of relic banded charnockite at the Mannantala quarry may be explained in either of the following two ways, i.e., either the breakdown of the charnockite into the garnet-biotite gneiss proceeded completely at the Mannantala quarry, or during the metamorphism when the banded charnockite formed at the Malayinkil and Kunnanpara quarries, no banded charnockite developed at the Mannantala quarry, possibly because of the nature of the original rocks or of the difference in the conditions of the metamorphism between the quarries.

Some events of the latest stage of the Malayinkil and Kunnanpara quarries may correspond to the fourth stage of the Mannantala quarry. The thermal conditions during

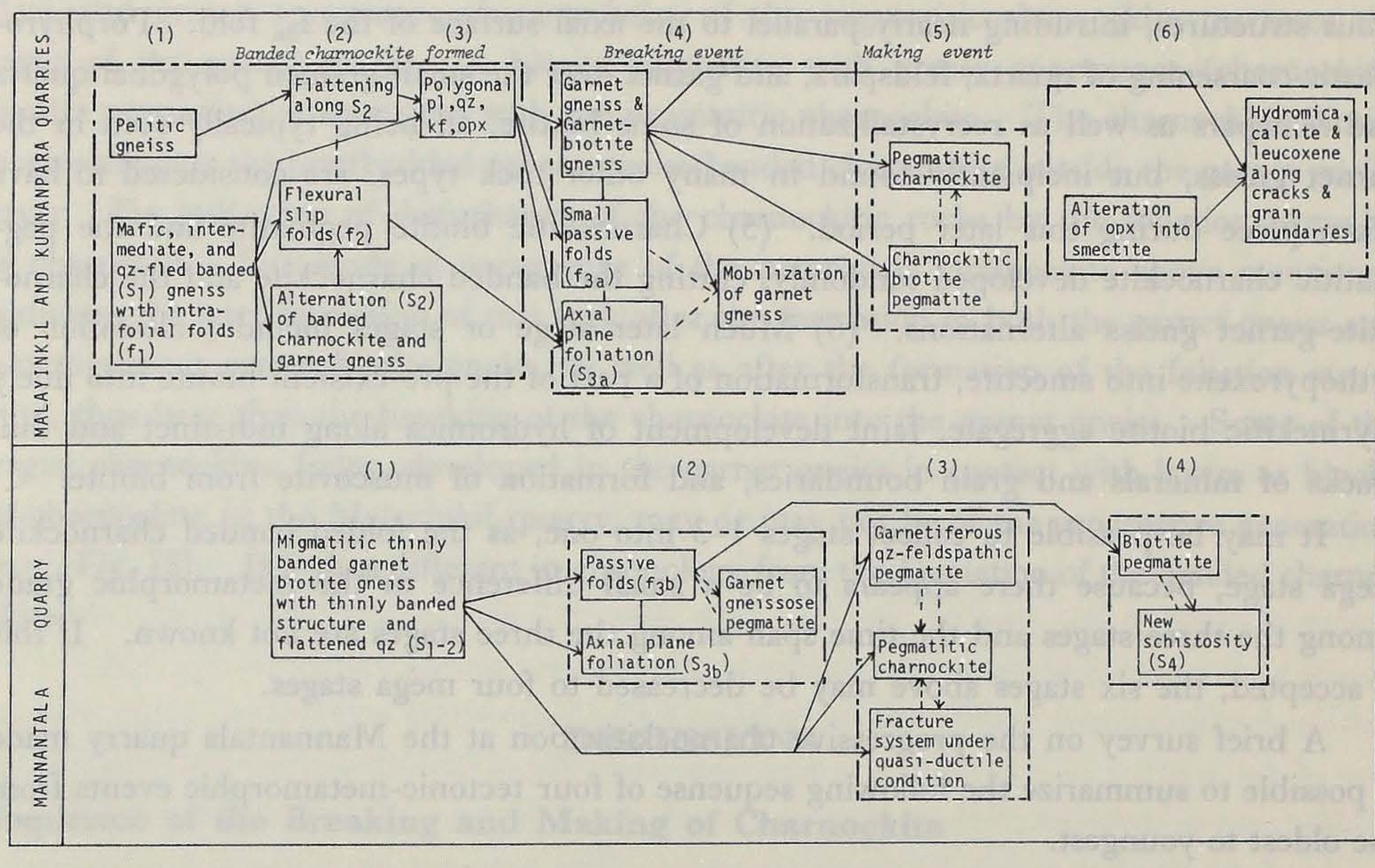

Fig. 32. Summary and comparison of structural and metamorphic events between the Malayinkil and Kunnanpala quarries and the Mannantala quarry.
Numbers in parenthesis refer to the stages of events mentioned in the text. Line with an arrow indicates that the top of the arrow is younger than the root, and solid line without an arrow indicates the synchronism of the two events, supported from data described in the text. Dashed line indicates the possibility of time relationship between the two events, although data are less. pl: plagioclase, qz: quartz, feld: feldspar, kf: potash feldspar, opx: orthopyroxene.

the biotite pegmatite intrusion might have caused dominant alteration.

In conclusion, the formation of the banded charnockite took place before the making of the pegmatitic charnockite; the making of the pegmatitic charnockite might have occurred later than the breaking of the banded charnockite as summarized in Fig. 32.

Regional Extent of the Breaking and Making of Charnockite in South India

SRIKANTAPPA et al. (1985) reported the wide occurrence of the progressive charnockitization throughout the southern Indian shield south of the Achankovil Linearment. They considered that the crustal segment south of the Achankovil Linearment represents a higher crustal level than the granulite terraine north of the Achankovil Linearment, because of the entire occurrence of the progressive transformation of the leptynitic gneisses to charnockite in the former area.

We have made also a field survey on areas around the Achankovil Linearment and further south including the well-known Pon Mudi quarry, and found that the earlier breaking of the pre-existent banded charnockite into the garnet-biotite gneiss and the garnet gneiss also took place there as well as the later making of pegmatitic charnockite (and foliated plutonic charnockite) from the gneisses (RADHAKRISHNA et al., in preparation). There is a possibility that the sequence of the breaking and making of charnockites in association with repeated deformational events as demonstrated in the present study is common throughout the southern Indian shield south of the Achankovil Linearment. It is noteworthy that PICHAMUTHU (1953) pointed out, from his extensive study on charnockitic rocks around Mysore, the sequence: banded charnockite formation under regional metamorphism - its retrogression to gneisses - formation of small-scale vein-type metasomatic charnockite. There is a possibility that the similarity in this sequence with that revealed in the present study reflects the common history of rocks of the area south of the Achankovil Linearment and the area around Mysore, in contradiction to suggestions by SRIKANTAPPA et al. (1985). The present study, however, is of the preliminary stage and of limited areas. Further detailed studies of the same area as well as the similar studies in somewhat wide areas of south Kerala is going on. The tectonic characterization of the crustal segment south of the Achankovil Linearment mentioned by SRIKANTAPPA et al. (1985) may be discussed after those future studies.

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